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The Vocabulary of Brain Potentials: Inferring Cognitive Events from Brain Potentials in Operational Settings

Illinois Univ. at Urbana-Champaign

August 1976

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THE VOCABULARY OF BRAIN POTENTIALS: INFERRING COGNITIVE EVENTS
FROM BRAIN POTENTIALS IN OPERATIONAL SETTINGS

Department of Psychology
University of Illinois at Urbana-Champaign
Champaign, Illinois 61820

August 1976

Combining Semiannual Technical Reports for
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University of Illinois at Urbana-Champaign

Department of Psychology

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Dr. Emanuel Donchin
Phone: (217) 333-3384

Signature: E. Donchin
Emanuel Donchin
Professor

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extraction techniques for ERP classification utilizing discriminant analysis is demonstrated. Experimental reports describing these research efforts are included in a final section.

Finally, an outline of ongoing and proposed research is presented that concerns application of ERP's to enhance performance in two applied contexts: The man-machine system environment characterizing the multi-task structure of the aircraft cockpit, and the field of computer aided instruction (CAI). In both settings, information provided by ERP's may supplement or replace that provided by operator responses, and allow the computer to affect adaptively the nature of the man-computer interaction. In the cockpit environment, the ERP can convey information concerning operator workload and the allocation of attention between tasks. In the CAI environment such information might concern the degree of learning of different items in the instructional set.

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PREFACE

In this document we report on the progress of the first year of a five year research program entitled "The Vocabulary of Brain Potentials: Inferring Cognitive Events from Brain Potentials in Operational Settings." This report combines the two semi-annual reports which concern the period July 1, 1975 to July 1, 1976. During the first six months of the project much of our effort was devoted to the design development and installation of the laboratory facilities described in Section B below. It seemed, therefore, more appropriate to include a description of these physical developments with the detailed report of the scientific work conducted during the remainder of the year.

The report is organized as follows. In Section A we present a narrative summary of the proposed experimental program as well as a summary of the laboratory's accomplishments during the reporting period. In Section B we present a detailed description of the Cognitive Psychophysiology Laboratory. The development of this unique resource has been supported almost entirely with funds provided under this contract. In Section C.1 we discuss the manner in which event related potentials (ERPs) may be used in the enhancement of the performance of man-machine systems, and outline our experimental plans. Section C.2 discusses in the same manner our plans for the incorporation of the ERP channel in the Computer Assisted Instructional Environment. These two sections summarize progress we made this year in identifying the framework for the use of Biocybernetic communication in operational environments and in developing initial test environments for the efficacy of this channel. Finally, Section D incorporates a series of detailed reports of experimental work completed during the reporting period. The work described is concerned with the elucidation of the vocabulary of the ERP and with the identification of ERPs at the single-trial level.

PROJECT PERSONNEL

PI: E. Donchin

Co Investigators: C. Wickens
K. Squires
N. Squires
R. Roman
L. Brenner

Consultant: D. Gopher

Research Assistants: E. Heffley
R. Horst
J. Israel
C. Johnson
R. Johnson
M. Kutas
G. McCarthy
H. Tennant

Project Engineer: T. Dee

Systems Engineer: R. Clapman

Electronic Technician: R. Klohr

Secretary: D. Skehen

Temporary and Part Time Help: S. Davis
P. Feldman
C. Malhotra
S. Petuchowski
J. Plebanski

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SECTION A

EXPERIMENTAL PROGRAM AND ACCOMPLISHMENTS

A.1 The Research Plan

In a proposal we submitted to ARPA on April 4, 1975 we introduced our research plans as follows.

Narrative SummaryA.1.1 Rationale

We have demonstrated that cognitive events can be inferred from cortical potentials which can be recorded through the scalp of intact, awake human subjects. Specific components of these event related potentials (ERPs) have been shown to be manifestations of such cognitive events as the preparation to perform a response, the preparation to intake and process information, the registration of a surprising event, or the processing of task relevant information.⁽¹⁾ With the application of powerful analytical techniques,⁽²⁾ we have in the past few months been able to greatly refine the resolution with which we can dissect the ERP into cognitively relevant components.⁽³⁾ We will refer to this phase of the work as the determination of the ERP vocabulary.

A brief summary of the available data on ERP components which are demonstrably associated with cognitive events follows.

An ERP is a transient series of voltage fluctuations induced in cortical tissue immediately following the occurrence of some critical inducing event. The ERPs can be induced by a variety of events such as the presentation of a stimulus, the occurrence of a response, a change in the rate of stimulation, etc. The amplitude of the response, as recorded from the scalp, is minute relative to the on-going brain wave activity (EEG), and it is only through the use of signal-averaging techniques that the waveform and characteristics of ERPs can be studied.

An ERP consists of a series of positive and negative peaks which continue for about 500 msec. The waveform, i.e., the sequence and timing of positive and negative peaks, depends on the eliciting event, on the state of the subject, and on the

placement of the recording electrodes on the scalp. For any given set of conditions ERPs are quite consistent between individuals, yet each individual tends to display a characteristic wave pattern. In the few published reports of ERPs recorded from the same individual over long periods the wave patterns proved remarkably stable.

Each peak-to-trough, or base-to-peak deflection appearing in the ERP at a consistent temporal interval following the eliciting event is called a "component." Many components are "exogenous," that is they represent the response of cortical tissue to the arrival of sensory volleys as a result of the activation of a peripheral sense organ. The exogenous components are often followed by what we shall call endogenous components. These represent cortical information processing invoked by the psychological demands of the context in which a stimulus is presented rather than by the physical properties of the stimulus. For example, we, and others, have shown that if a stimulus provides task-relevant information to a subject the ERP elicited by that stimulus will be characterized by a large positive going wave with a latency to the peak of about 300 msec. We call this component P300.

With few exceptions, ERP components are labeled by a <character><number> designation. The character indicates the polarity of the component (P = positive, N = negative), the number refers to the modal delay between the eliciting event and the peak of the component.

1. N100. Present in ERPs elicited by all stimuli of moderate and high intensities. Recent evidence suggests that the amplitude of N100 is a function of the degree to which subject is attending selectively to the modality in which the stimuli are presented.
2. N190. This ERP component, studied in detail in our laboratory, seems to be elicited whenever a rare, or unexpected, event occurs. It is of particular interest because it can be elicited by stimuli which are in fact in the periphery of the subject's attention span. Due to the fairly recent discovery of N190 the details of its relationship to psychological variables have yet to be worked out.

3. P300. This is the most robust of the endogenous ERP components. In more than a decade of research it has been recorded in many laboratories, in a large number of situations. It seems to be most reliably recorded in association with task-relevant, rare stimuli and seems to reflect in amplitude the complexity of the information processing invoked by the stimulus.
4. "Slow Wave". We have established that the P300 component is often followed by a slow potential shift which is affected by the same variables which are known to affect the P300 except that it has a different scalp distribution. Whereas P300 appears largely as a positive going potential peaking on the parietal (posterior) scalp, the slow wave is positive going in parietal electrodes and negative going in frontal electrodes.
5. The Contingent Negative Variation (The CNV). This wave precedes anticipated events in response to which the subject will have to perform a demanding motor, or mental, act. It is very reliably recorded during the warning interval (foreperiod) in a reaction time task, in the form of a negative ramp beginning about 400 msec after the warning stimulus and peaking just prior to the response-commanding (imperative) stimulus.
6. "Readiness Potential" (RP). This is a CNV-like wave. It is distinct only in the sense that it appears prior to self-paced voluntary responses. Its occurrence is independent of the presence of an eliciting, or a command stimulus. The relationship between the RP and the CNV is a subject of much active research and some controversy.

The determination of the ERP vocabulary consists of defining with ever increasing resolution the specific psychological variables which determine the amplitude and scalp distribution of these potentials. It is also necessary to develop techniques for dissecting any given waveform into its constituent components. These have been the main charges of our past research and we feel we made substantial progress. Specifically, we have developed a powerful combination of Principal Component analysis and

analysis of variance which has enabled us to clarify the relationship between ERP components. (4)

As the known vocabulary of ERPs develops it becomes increasingly likely that the ERP might play an important role in man-computer interactions. If the vocabulary can be "understood" by a computer, and there is no doubt that it can, then an important communication link can be established between the operator and his equipment. At least three advantages are apparent in such a communication channel.

1. As the ERPs seem to, at least in part, manifest events in the nonverbalized substrate of cognition they may provide information which cannot be otherwise communicated by the operator.
2. The immediate access ERP components provide into the subject's cognitive world suggest that they might enhance communication speed.
3. The strong presumptive evidence that an individual's ERP is unique suggests that these potentials might constitute an ongoing self authenticating component of the communication process.

The project plan proposed here capitalizes on the success of the first two years of our ARPA support and is designed to develop realistic implementations of biocybernetic communication systems in simulated operational environments.

We see the following specific tasks.

- a. Refine our present knowledge of the ERP vocabulary. Particular emphasis will be placed on the newly discovered Ni90 and "slow wave" components, as well as on consolidating our understanding of P300 as a measure of the feedback subjects derive from specific stimuli.
- b. Test the utility of the well established vocabulary in enhancing performance of operators controlling complex devices (with our major model being the aircraft cockpit).
- c. Test the utility of the vocabulary in the Computer Assisted Instruction environment. Here the model will be the PLATO lesson and our goal the facilitation of interaction between the student and the teaching console.

The major difficulty in developing the ERP as a communication channel is the very low signal to noise ratio in the channel.⁽⁵⁾ The ERPs are minute in amplitude relative to the "polyneuronal roar" of the ongoing EEG activity. In determining the vocabulary, signal to noise ratios can be enhanced through the use of signal-averaging. This technique relies, of course, on the repeated occurrence of the cognitive events as well as on the computer's precise knowledge of their time of occurrence. While this procedure is adequate for vocabulary identification it will not do for practical communication in operational environments. In these we must be able to identify the occurrence of ERP components in the ongoing EEG activity immediately following single occurrences of the specific events. The problem then becomes one of developing single-trial signal extraction techniques (STSE).

We have been developing STSE procedures for some time.⁽⁶⁾ Work conducted with our present ARPA support indicates that Stepwise Discriminant Analysis (SWDA) procedures allow correct classification of trials at a hit rate of 80 percent. This hit rate is based on a crude application of SWDA. It is likely that STSE could be greatly improved by combining data from multiple channels and by prefiltering the ongoing EEG activity to eliminate energy in the "noise" bandwidth before discrimination begins. Development work on STSE could not begin in earnest prior to the identification of the vocabulary and it is contingent on computational power which will be at our disposal according to present project plans. We intend to devote much effort to the single-trial problem. The development of a STSE is contingent also on the development of refined techniques to increase signal to noise ratio in the real-time evaluation of performance. In fact, failure to "correctly" detect ERPs on single trials may often be due to variability in the concomitant performance variables as much as it is due to inherent "noise" in the EEG. Thus the development of STSE techniques requires a conjoint measurement of performance and EEG variables. We need techniques which lead towards sufficiently accurate definitions and measures of single "performance" events, which can then be correlated with their ERP counterparts. The investigation of this

problem and the development of such techniques will be directed by the Aviation Research Laboratory. Both research programs will be joined in an effort to improve the real-time evaluation of cognitive and behavioral events. All data collected in all experiments to be conducted in the laboratory would provide a data base for the development of STSE procedures. The operational environments in turn will be used for specific demonstrations of these procedures as they emerge.

A.1.2 Research Plan

Three concurrent activity streams will be maintained during the next year.

- a. The procurement and installation of hardware and software for recording ERPs in simulated cockpits and in a CAI installation.
- b. Intensive development of STSE techniques and the implementation of at least one demonstration in which a STSE is used in biocybernetic communication.
- c. Continuation of work on vocabulary identification, using our existing facility.

It should be emphasized that even though a major development effort will be required by activity stream a, we plan to maintain a steady level of effort in the other two categories. If the proposed personnel contingent is approved the installation of the new laboratory can be accomplished with no reduction in our present rate of progress. Moreover, we intend to support the use of our facilities by remote investigators as the need arises.

Footnotes

- (1) Gilden, L., Vaughan, H. G., Jr., and Costa, L. D. Summated human EEG potentials with voluntary movements. Electroencephalography and Clinical Neurophysiology, 1966, 20: 433-438.

Walter, W. G. Slow potential changes in the human brain associated with expectancy, decision and intensification. Electroencephalography and Clinical Neurophysiology, 1967, Suppl. 26: 123-130.

- Vaughan, H. G., Jr., Costa, L. D., and Ritter, W. Topography of the human motor potential. Electroencephalography and Clinical Neurophysiology, 1968, 25: 1-10.
- Deecke, L., Scheid, P., and Kornhuber, H. H. Distribution of readiness potential, pre-motion positivity and motor potential of the human cerebral cortex preceding voluntary finger movements. Experimental Brain Research, 1969, 1: 158-168.
- Kutas, M. and Donchin, E. Studies of squeezing: Handedness, responding hand, response force, and asymmetry of readiness potential. Science, 1974, 186: 545-548.
- Cohen, J. and Walter, W. G. The interaction of responses in the brain to semantic stimuli. Psychophysiology, 1966, 2: 187-196.
- Jarvilehto, T. and Fruhstorfer, H. Differentiation between slow cortical potentials associated with motor and mental acts in man. Experimental Brain Research, 1970, 11: 309-317.
- McAdams, D. W. and Rubin, E. H. Readiness potential, vertex positive wave, contingent negative variation and accuracy of perception. Electroencephalography and Clinical Neurophysiology, 1971, 30: 511-517.
- Picton, T. W. and Low, M. D. The CNV and semantic content of stimuli in the experimental paradigm: Effects of feedback. Electroencephalography and Clinical Neurophysiology, 1971, 31: 451-456.
- Sutton, S., Braren, M., Zubin, J., and John, E. R. Evoked-potential correlates of signal uncertainty. Science, 1965, 150: 1187-1188.
- Tueting, P., Sutton, S., and Zubin, J. Quantitative evoked potential correlates of the probability of event. Psychophysiology, 1971, 7: 385-394.
- Squires, K., Hillyard, S., and Lindsay, P. Cortical potentials evoked by confirming and disconfirming feedback following an auditory discrimination. Perception and Psychophysics, 1973, 13: 25-31.

- Sutton, S., Tueting, P., Zubin, J., and John, E. R. Information delivery and the sensory evoked potential. Science, 1967, 155: 1436-1439.
- Donchin, E. and Cohen, L. Average evoked potentials and intramodality selective attention. Electroencephalography and Clinical Neurophysiology, 1967, 22: 537-546.
- Smith, D. B. D., Donchin, E., Cohen, L., and Starr, A. Auditory average evoked potentials in man during binaural listening. Electroencephalography and Clinical Neurophysiology, 1970, 28: 146-152.
- Hillyard, S., Squires, K., Bauer, J., and Lindsay, P. Evoked potential correlates of auditory signal detection. Science, 1971, 172: 1357-1360.
- (2) Donchin, E. A multivariate approach to the analysis of average evoked potentials. IEEE Transactions, Bio-medical Engineering, 1966, BME-13: 131-139.
- Donchin, E. Discriminant analysis in average evoked response studies: The study of single trial data. Electroencephalography and Clinical Neurophysiology, 1969, 27: 311-314.
- Donchin, E. Data analysis techniques in average evoked potential research. In E. Donchin and D. B. Lindsley (Eds.), Average evoked potentials: methods, results, and evaluations. NASA, SP-191, Washington, D.C., 1969, 199-236.
- Donchin, E., Callaway, E. III, and Jones, R. T. Auditory evoked potential variability in schizophrenia. II. The application of discriminant analysis. Electroencephalography and Clinical Neurophysiology, 1970, 29: 429-440.
- Donchin, E., Kubovy, M., Kutas, M., Johnson, R. Jr., and Herning, R. Graded changes in evoked response (P300) amplitude as a function of cognitive activity. Perception and Psychophysics, 1973, 14: 319-324.
- Donchin, E. and Herning, R. A simulation study of the efficacy of stepwise discriminant analysis in the detection and comparison of event related potentials. Electroencephalography and Clinical Neurophysiology, 1975, 38: 51-68.

- (3) Donchin, E., Tueting, P., Ritter, W., Kutas, M., and Heffley, E. On the independence of the CNV and the P300 components of the human averaged evoked potential. Electroencephalography and Clinical Neurophysiology, 1975, 38: 449-461.
- Squires, K., Donchin, E., Herning, R. I., and McCarthy, G. On the influence of task relevance and stimulus probability on event-related-potential components. Electroencephalography and Clinical Neurophysiology, 1976, in press.
- (4) Donchin, E. A multivariate approach to the analysis of average evoked potentials. IEEE Transactions, Bio-medical Engineering, 1966, BME-13: 131-139.
- Donchin, E., Tueting, P., Ritter, W., Kutas, M., and Heffley, E. On the independence of the CNV and P300 components of the human averaged evoked potential. Electroencephalography and Clinical Neurophysiology, 1975, 38: 449-461.
- Squires, K., Donchin, E., Herning, R. I., and McCarthy, G. On the influence of task relevance and stimulus probability on event-related-potential components. Electroencephalography and Clinical Neurophysiology, 1976, in press.
- (5) Geisler, C. D. Average response to clicks in man recorded by scalp electrodes. MIT Research Laboratory of Electronics, Technical Report, 1960.
- Donchin, E. Brain electrical correlates of pattern recognition. In Signal Analysis and Pattern Recognition in Bio-Medical Engineering, (Inbar, G., Ed.). John Wiley, 1975, 199-218.
- (6) Donchin, E. Discriminant analysis in average evoked response studies: The study of single trial data. Electroencephalography and Clinical Neurophysiology, 1969, 27: 311-314.
- Donchin, E., Callaway, E. III, and Jones, R. T. Auditory evoked potential variability in schizophrenia. II. The application of discriminant analysis. Electroencephalography and Clinical Neurophysiology, 1970, 29: 429-440.

Donchin, E. and Herning, R. I. A simulation study of the efficacy of step-wise discriminant analysis in the detection and comparison of event related potentials. Electroencephalography and Clinical Neurophysiology, 1975, 38: 51-68.

A.2 Summary of Accomplishments

The following summarizes the results of the research conducted during the reporting period in this laboratory with the support of Contract #US Navy N00014-76-C-0002 entitled "The Vocabulary of Brain Potentials: Inferring Cognitive Events from Brain Potentials in Operational Settings." Most generally stated we have:

1. Greatly expanded our knowledge of the P300 component of the human event related brain potential (ERP), to the extent that we now have a fairly good understanding of the variables which control P300 amplitude and latency. Thus, strong inferences can now be drawn from this ERP component about an operator's cognitive activity. More limited conclusions were developed with respect to other elements of the ERP vocabulary.
2. Demonstrated conclusively that P300 can be detected without recourse to signal averaging using stepwise discriminant analysis.
3. Developed the paradigms in which the utility of a biocybernetic communication channel could be evaluated within a pursuit tracking environment and within the CAI environment. Initial experimentation in both environments has been concluded.

These general statements are based on the following results:

A.2.1 ERP Vocabulary Elaboration

In reviewing the following results the reader should keep in mind that all pertain to the ERP elicited by task-relevant stimuli. The same sequence of physical

stimuli presented to the same subjects while they perform tasks to which the stimuli are not relevant fail to elicit a P300. It is this sensitivity of P300 to degrees of task relevance which implies its potential utility in the Biocybernetic applications we plan for FY 77 and the following years.

a. We have discovered that the amplitude of P300 is exquisitely sensitive to momentary variations in a psychological variable we choose to call "expectancy." We have demonstrated that the "expectancy" of an event varies as a function of three variables, the number of like events occurring in the recent past, the specific structure of the preceding series of events and the a priori probability of the event. Using a mathematical model based on these assumptions about expectancy we can explain 80% of the variability of P300. Specifically, the more "unexpected" an event, the larger the amplitude of P300 it elicits (Squires, Wickens, Squires & Donchin, Science, in press; see also Section D.1).

b. We have shown that the relation between P300 and expectancy is independent of the modality of the stimulus used to elicit the P300 at least when we use visual and auditory stimuli (Squires, Petuchowski, Wickens & Donchin, in preparation^{*}).

c. We completed a parametric study of the relationship of P300 to the a priori probability of an event. The data confirm the results described in (a) above and establish that the relation of P300 to expectancy holds over the entire range of a priori probabilities from 0.10 to 0.90. Furthermore, the data support the assumption made in our model that the effects of a priori probability and of sequential constraints interact in an additive manner to determine the amplitude of P300 (Duncan-Johnson & Donchin, in preparation).

d. We investigated ERPs elicited by compound stimuli, that is by simultaneously presented auditory and visual stimuli. This study enabled an analysis of the behavior of P300 when stimuli deliver redundant and non-redundant information. The data

* Manuscripts are cited as being in preparation when drafts are ready for internal review.

suggest that it is possible to infer from the amplitude and latency of P300 to which element of a stimulus compound a subject is directing attention (Squires, N., Squires, K., Donchin & Grossberg, submitted for publication; Section D.2).

e. As P300 seems to be enhanced by stimuli which resolve the subject's uncertainty, it was important to determine if resolving temporal uncertainty (i.e., determining when an event will occur) is as effective as resolving event uncertainty (determining which event will occur). We completed a study which demonstrated that P300 is not affected by temporal uncertainty (McCarthy & Donchin, in press; Section D.3).

f. We have begun to investigate the role of the feedback value of stimuli in determining P300 amplitude. When a stimulus which serves to indicate to the subject whether or not he has performed some task correctly elicits a P300, it turns out that the amplitude of P300 varies with the difference between the intensity of the stimulus which indicates to the subject that he performed the task correctly and that which indicates errors. The bigger the intensity difference between the "correct" and "error" indicators the larger the P300 elicited by these stimuli. These data suggest that the utility of a stimulus in a feedback loop affects the amplitude of P300.

g. We have shown that P300 latency is determined by the duration of the cognitive activity required of the subject before he can correctly categorize the eliciting event. This result is very important. It establishes that the "late positive components" whose latency may range from 300 msec to over 600 msec after the physical eliciting stimulus are all instances of the P300 component. This experiment was also important in demonstrating that different physical stimuli which belong to the same semantic category can elicit the same P300, if the subject performs the same cognitive operation on the stimuli (Kutas & Donchin, in press; Section D.4).

h. An important aspect of the data obtained in all the experiments described above is that in all cases P300 shows the same scalp distribution, with a maximum over the parietal lobe ("association cortex"). Analysis of the scalp distribution of ERP

components is emerging as a major tool in the interpretation of the data.

i. We conducted a detailed analysis of the degree to which slow negative preparatory potentials will show a differential distribution over the two hemispheres as a function of the nature of the processing required of the subject (verbal vs. spatial tasks). We do find such lateralization of the preparatory potentials. However, it occurs only when the processing demands vary from trial to trial. No changes are observed when the processing demands are uniform over the trial. Our data suggest that the lateralization of the potentials changes in the amplitude of the potentials recorded over the left hemisphere rather than reciprocal changes in the activities of both hemispheres (Donchin, Kutas & McCarthy, in press; see D.5).

j. In a detailed analysis of all ERP components elicited during a categorization task we have been able to dissociate clearly two additional endogenous components of the ERP, the N200 and the Slow Wave. These data confirmed and clarified reports from other laboratories. The N200 component promises to allow monitoring of fluctuations in the focus of attention (Squires, Donchin, McCarthy & Herning, in press; see D.6).

A.2.2 Single Trial Analysis Techniques

a. Sixteen subjects were presented with a series of tones, each tone either 1000 Hz or 1500 Hz. The a priori probability of the 1500 Hz tone was 0.10. These rare tones, elicit, of course, a P300. When these data are used to develop for each subject, a discriminant function we find that we can classify correctly over 80% of the individual stimuli obtained from each subject (Squires, Donchin, in press; see D.7).

b. The generality of the discriminant function was evaluated by developing a cross-subject function using the data from all subjects and testing this function both on the data of each of the 16 subjects and on data obtained from seven new subjects. In all cases the classification performed quite well, percentages of correct classifications ranging from 64 to 77% (see D.7).

c. While an 80 correct classification rate is remarkable we pursued the possibility that the "misclassifications" reflect real changes in the subject's response to the external stimulus. The search led to the discovery of the dependence of P300 on the sequence of preceding stimuli (A.2.1a). We then conducted a study in which the a priori probabilities of the two stimuli were equal. The discriminant functions are now developed on the basis of the two extreme expectancy conditions (that is, we discriminate between all stimuli preceded by four identical stimuli and all stimuli preceded by four different stimuli). This classification in terms of expectancy appears to identify correctly the expectancy associated with each stimulus in the sequence. This study demonstrates that single trial identification of the subject's cognitive response to the stimulus is feasible.

d. We have shown that discriminant functions developed on the basis of auditory sequences can be successfully applied to visual stimuli and vice versa.

A.2.3 Operational Environments

a. Two studies were completed, each using six subjects, in which ERPs were recorded while the subjects performed a pursuit tracking task. The difficulty level of the tracking was systematically manipulated. The experiments helped to identify the problems encountered during such tests. Most of the problems have by now been solved and systematic experimentation has begun. The data obtained in the first two experiments are inconclusive and indicate several sources of uncontrolled variation in subject motivation and performance which have been corrected. The data, however, do indicate that ERP waveform changes with subject's task load. However, the patterns varied from subject to subject. In an attempt to force a more uniform strategy on the subjects the experiment has been redesigned using compensatory rather than pursuit tracking tasks.

b. Several experiments were conducted in which ERPs were obtained from the subject interacting with a Plato terminal. Again the problems associated with recording in this complex environment have been identified and many were solved. These

studies have led to the selection of the Drill and Practice paradigm as the prototypical CAI task for testing the efficacy of the biocybernetic channel. (Drill and Practice is the set of procedures whereby a student is helped in memorizing lists of items.)

In summary then, we have been successful in our pursuit of the vocabulary of ERPs and in developing the techniques for real time use of the endogenous components of the ERP. In addition, at the end of this first year of the project we completed on schedule the development of the facilities for studying ERPs in semi-operational environments and are already deep into the experimental phase of this aspect of the program.

A.3 Analysis of Milestones

We list here the project's milestones as outlined in the original proposal for the reporting period and review the extent to which we attained each.

Milestones

July 1, 1975

- Issue formal purchase orders for all required equipment.
Done.

- Install Plato terminal and begin ERP recordings.
Done.

September 1, 1975

- Begin recording ERP in Aviation Research Lab's GAT-2 Simulator.

The feasibility of such recordings has been established. However, due to the cost involved in the use of the GAT-2 and other ARL facilities it was decided to restrict all experimental activity to the premises of the Cognitive Psychophysiological Laboratory during the first two years of the project.

- Complete study of Cross-modal P300 as well as CNV-RP studies. Submit for publication.

Done.

- Provide on-line demonstration of the feasibility of single trial techniques in the detection study.

Done. We used the "odd-ball" paradigm instead of the detection paradigm.

- Complete installation of all laboratory equipment system. Begin software installation.

Done.

December 1, 1975

- Complete installation of 11/70 system.

Done, except that instead of the 11/70 we acquired and installed the Harris Slash 4 (to be replaced by a Slash 7 in August 76).

- Complete first ERP/tracking study.

Done.

April 1, 1976

- All 4 computers in the network fully implemented and interconnected.

Partially done. All computers are functioning. The computers are also interconnected using 300 baud lines. The DECNET software, however, was delivered by DEC in May, 1976 (8 months behind schedule) thus the full implementation of an online network has been delayed and is now scheduled for September, 1976.

- Connection to ARPANET complete.

It was decided not to connect the laboratory to the ARPANET. The Harris' computational power made us fairly independent of off-site computers.

- Specification of CAI-ERP studies completed.

Done.

- At least 4 ERP vocabulary studies submitted for publication.

Done.

July 1, 1976

- PDP 11/70 and rest of network used in at least one on-line experiment.

Awaits installation of DECNET. However, all links in the chain on each of the networks components is now fully functional.

- Standard procedures available for all ARPANET data storage and data analysis.

Implemented on the Harris.

- STSE procedures standardized for rest of project.

Partially done.

- ARL recording techniques fully developed. At least one ERP experiment completed at ARL.

Postponed. Budget does not permit and project needs do not justify use of simulator. These activities are now scheduled for FY 78. Note that ARL personnel are actively involved in project and in experiments at CPL.

SECTION B

THE FACILITIES OF THE COGNITIVE PSYCHOPHYSIOLOGY LABORATORY

B.1 Introduction

The Cognitive Psychophysiology Laboratory (CPL) is dedicated to the study of electrocortical, and other psychophysiological, manifestations of cognitive processes. The Laboratory's primary interest is in elucidating the functional significance and physiological basis of such endogenous components of Event Related Brain Potentials as P300 and the CNV. This interest is expressed within the framework of an attempt to develop Biocybernetic man-machine communication channels which by enriching the information available to a computer-driven system about its operators, may enhance the performance of the system.

The Laboratory's main source of support is the Cybernetic Technology Office of the Advanced Research Projects Agency of the Department of Defense. The CPL's contract with ARPA is one of several contracts which ARPA's Biocybernetics Program, managed by Dr. Craig Fields, has awarded to investigators in universities and other research organizations. In addition to its own research program, the CPL serves to test the applicability of findings developed by other investigators in the simulated-operational environments it has developed.

The CPL is directed by Professor E. Donchin and its scientific staff consists of collaborating faculty members, post-doctoral Research Associates and graduate students. These are aided by a technical support staff of engineers, programmers, technicians and secretaries. The Laboratory is fully integrated in the Department of Psychology of the University of Illinois. Appointments at the Laboratory at all levels are made through the Department and all personnel must meet the Department's acceptability criteria.

B.2 Description of Facilities

B.2.1 General

The Cognitive Psychophysiology Laboratory occupies over 3500 square feet in the Department of Psychology's building. The building, opened in 1969, has been well designed to meet the needs of research in Psychology. There are extensive shop facilities, a good animal colony, computer facilities with easy access for data paths from all parts of the building and good control over illumination and other environmental conditions. The laboratory wing is exceptionally free of electrical and electrostatic noise, easing the burden of the psychophysiolgist.

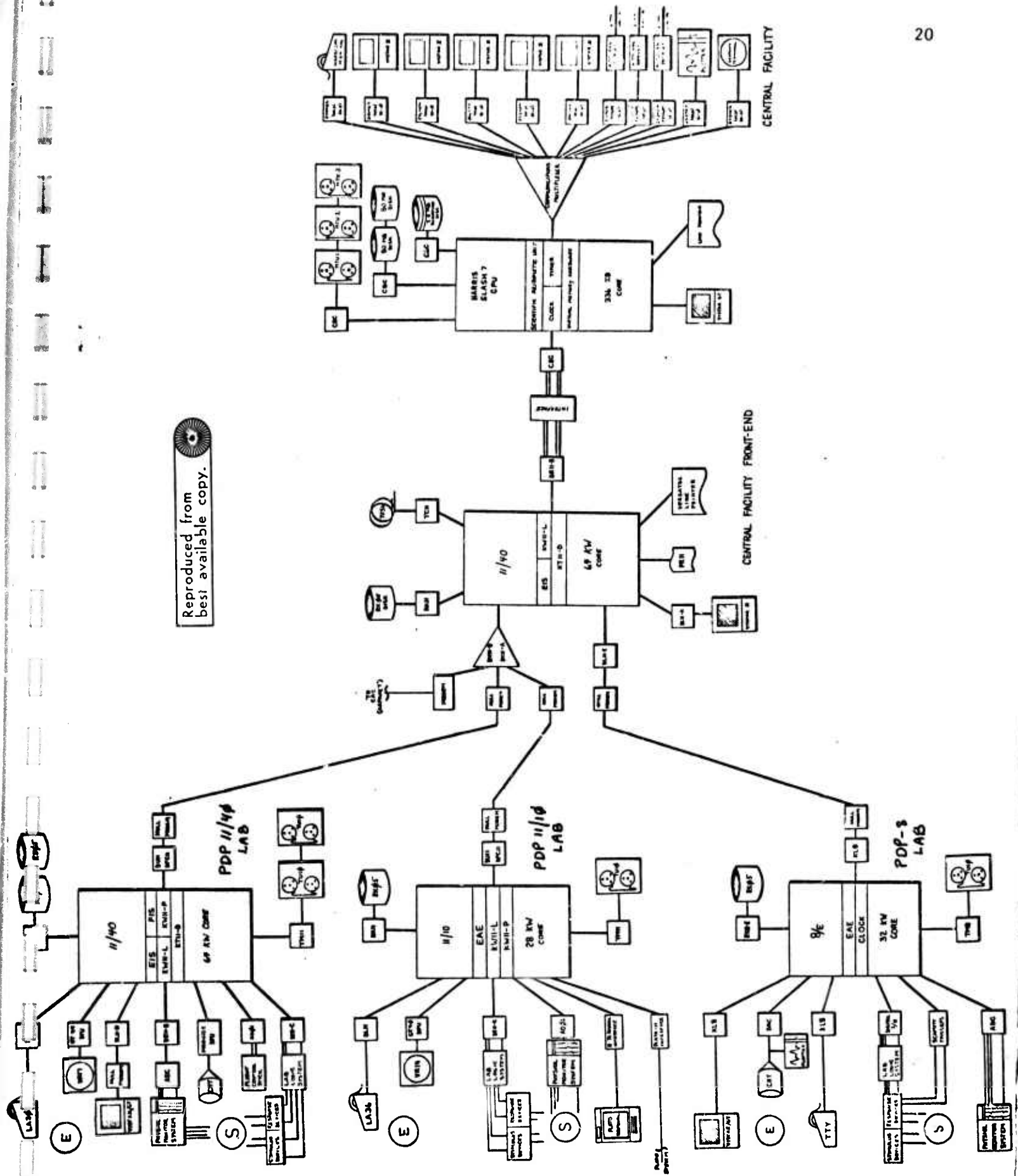
The Department of Psychology has been generous to CPL in allocating both laboratory and office space. Cramped but adequate office-space is available for the entire staff and for data-storage and data-analysis. The laboratory space houses the CPL's Harris Slash 7 computer, three computer-based laboratories and such auxillary services as a shop and a computer terminal room.

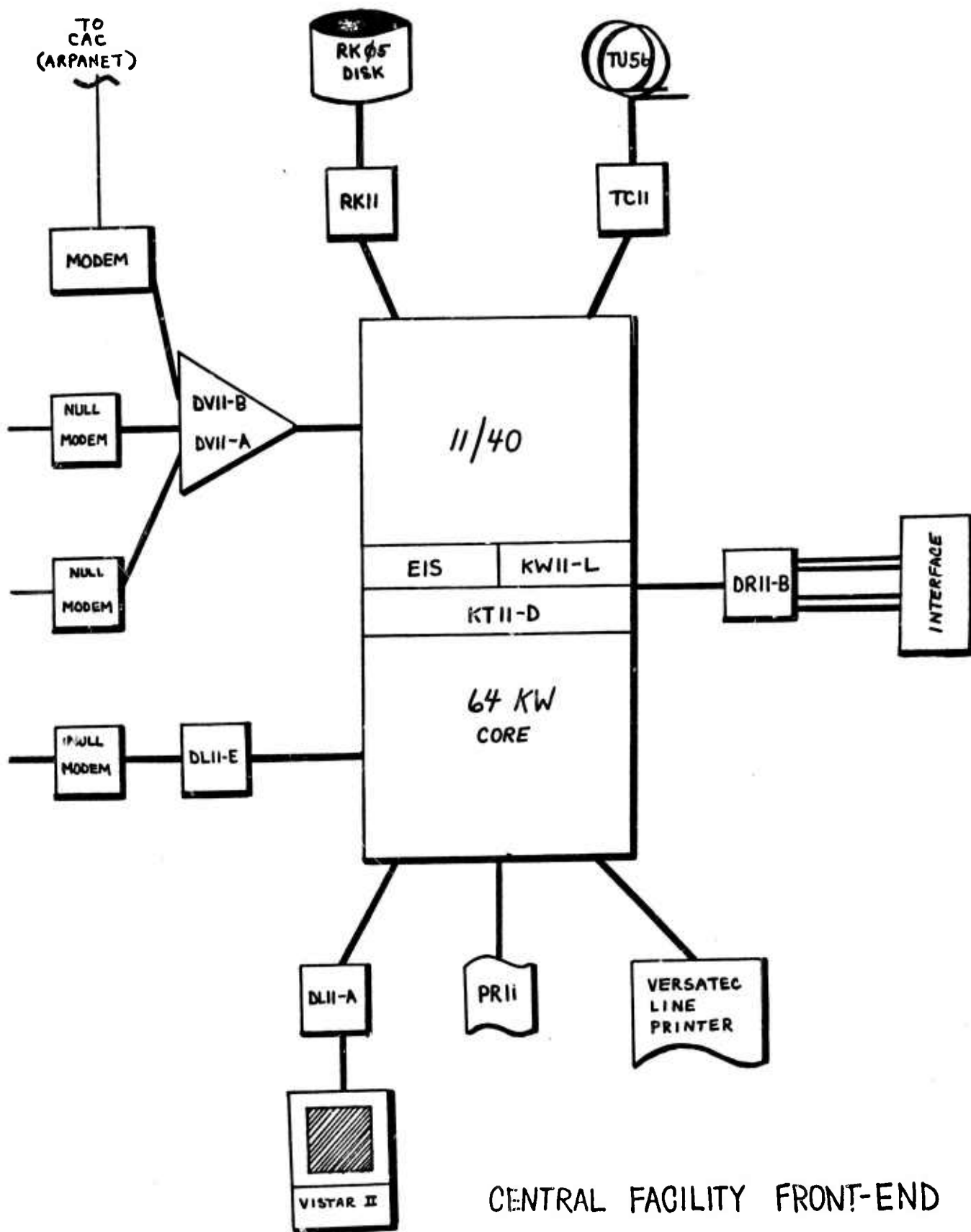
B.2.2 The Network: Overview

The functional organization of the laboratories is shown in Figure 1. A Star network of computers supports the laboratories. At the center of the star is a PDP 11/40 computer whose prime function is to manage the operations of the Network. This computer is referred to as the Front End (FE) and is driven by the RSX11D/DECNET package supplied by Digital Equipment Corporation. Through the services of DECNET it interconnects the three laboratory computers with each other, and all three with the Harris Slash 7. [Note: While all components of the Network are operational when this is written (7/1/76), the DECNET software has been installed but the Harris - DEC interface is yet to be completed. Implementation is underway and the Network is expected to be operational by Sept. 30, 1976.]

One of the four outer points of the star is the Harris computer. This is a "Midi" computer, fully described below, which can support most of the data reduction and data processing needs of the Laboratory. This it can do both for previously acquired

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data or online through the Network.

At the other three nodes are three computers, each supporting a Psychophysiological Laboratory. These use a PDP11/40 (GT44) supporting a Human Performance Lab, a PDP 11/10 (GT40) which is attached to PLATO, the University of Illinois' Computer Assisted Instruction System, and a PDP 8/e which supports both a standard experimental psychology lab, and a facility for studying the relation between cortical activity and motor behavior in humans.

B.2.3 The Laboratories

B.2.3.1 General Features

All three labs share the following features:

- (a) All experimental control and data acquisition are under computer control.
- (b) The laboratory computer can support a moderate degree of on-line data analysis and extensive information on the progress of the experiment can be provided on-line to the investigator.
- (c) Experimental control, data-acquisition and on-line feedback are all controlled by Fortran-callable assembler subroutines. Thus while the computer's speed and power can be applied to its tasks the investigator need program in FORTRAN only.
- (d) Data acquisition is all-digital. Both raw data and processed data are stored on 9-track, industry compatible, magnetic tapes during the experimental sessions. (Analog data recording is still required in the 8/e supported laboratory. This lab will be converted to all-digital operation in 1977.)
- (e) Each laboratory has the following components:
 - (1) Stimulus generation and response-logging equipment.
 - (2) Psychophysiology recording system (mostly for EEG).
 - (3) A computer.

(4) Experimenter display and control station.

The following sections will briefly describe each of the three laboratories.

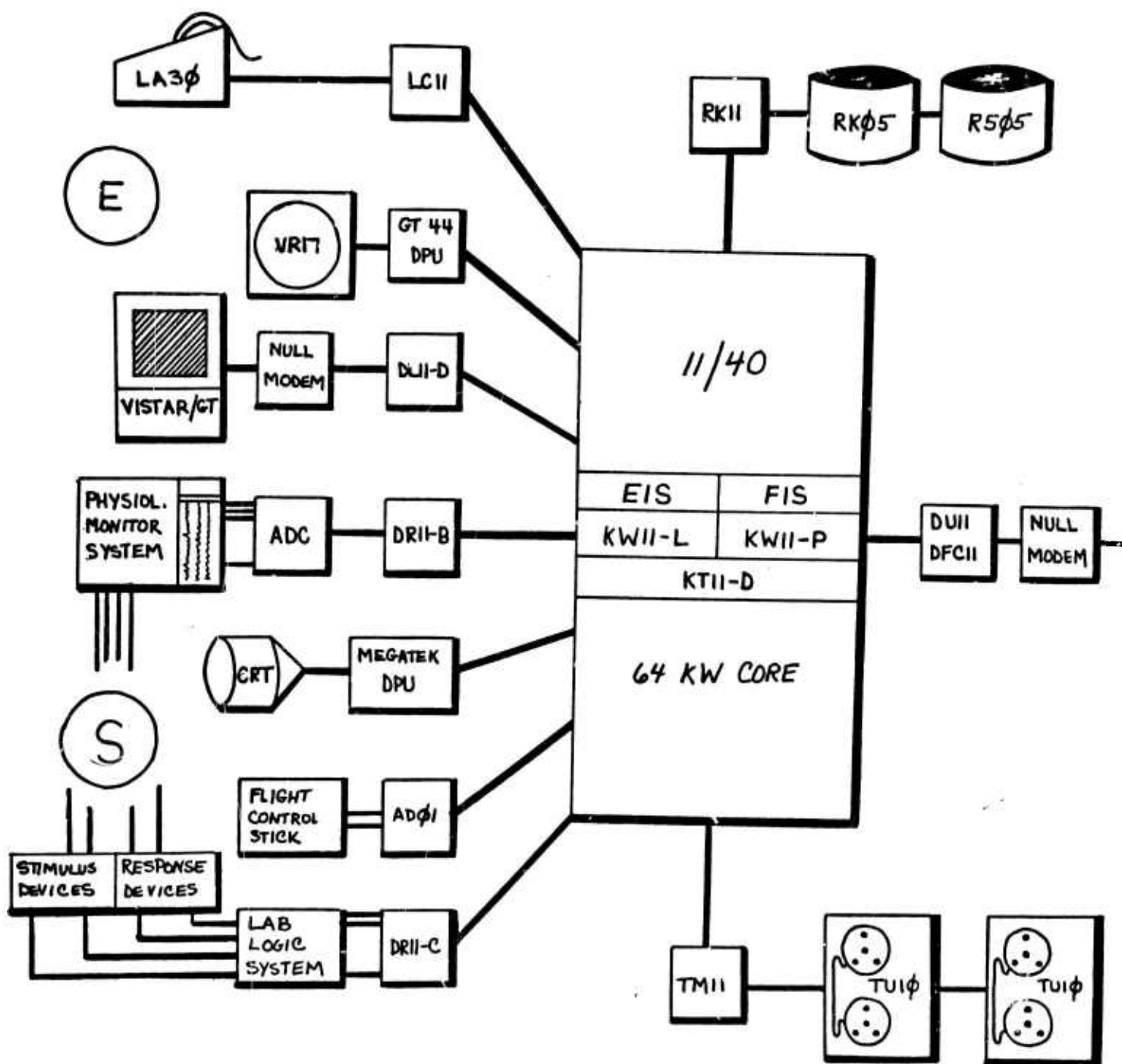
B.2.3.2 The Human Performance Laboratory

A detailed block diagram of the lab is shown in Figure 2. At the core of the lab is a GT44 computer system. This is a PDP 11/40 with a special display processor (VT17). Notable is the extensive configuration of this GT44. It is equipped among other things with memory management, 54K of core, 2 disks and 2 tape drives. A wide range of stimulus generating equipment driven by an Iconix system is available (e.g., a 4 field Tachistoscope, tone generating equipment, etc.). In addition, a Megatek display is used in generating a tracking display. Targets following fairly complex paths are generated on an oscilloscope screen and the subject can control the screen display via a joystick according to the experimenter's instructions.

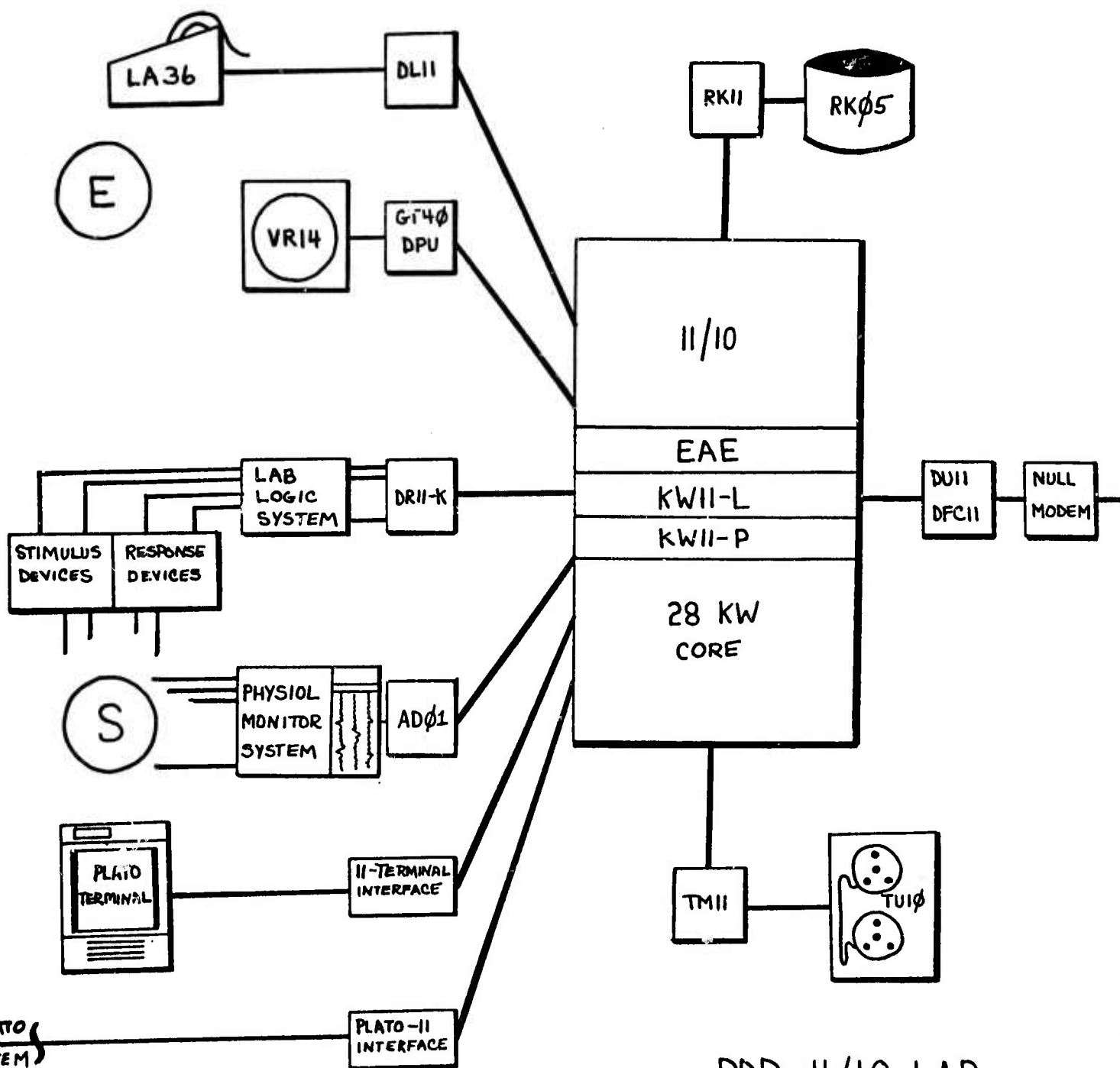
As an example of the laboratory's capacity we describe one of our current experiments: Subject is performing a two-dimensional tracking task. The target is driven by the computer which also monitors the subject's joystick. The target behavior is changed adaptively, on-line, to achieve a prespecified performance level by the subject. While tracking the target the subject is presented with a series of tones, each of which may be either high (1500 Hz) or low (1000 Hz), according to a computer determined random schedule. The subject's EEG is digitized continuously from 12 electrodes. Epochs of EEG just preceding and just following the tones are stored on digital tape. These same epochs can be displayed to the investigator. At the same time the average event related potential is computed, stored on another digital tape and may be displayed to the investigator. A record of the subject's performance both on the tracking task and on a secondary task associated with the tones is also kept on tape. A summary of the session results can be printed out. At anytime during the session the investigator can easily change any of the parameters controlling the experimenter.

B.2.3.3 The PLATO Laboratory

A block diagram of the laboratory is shown in Figure 3. The figure shows



PDP-11/40 LAB



PDP 11/10 LAB

the final configuration of this lab which should be completed by September 1, 1976. A more limited configuration is currently in use.

The laboratory is based on a GT40 (which is an 11/10 with a display processor), with 16K of core, a disk and one digital tape deck. Its mode of operation is much like that of the Human Performance Lab with the limitations imposed by its smaller configuration.

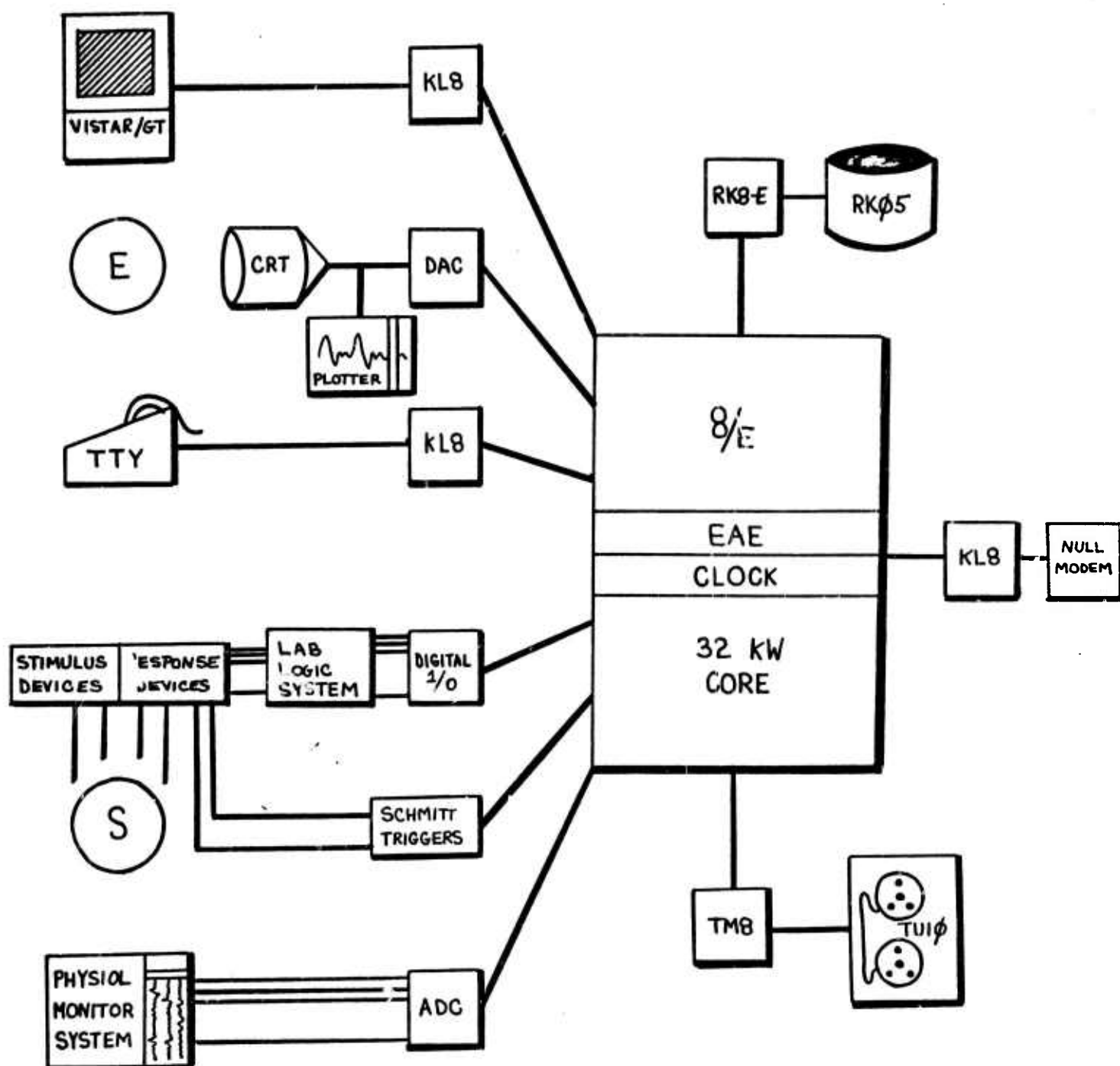
The laboratory, however, is unique in that it serves as an intelligent terminal for the PLATO system. Its intelligence extends to the capability of recording psychophysiological responses associated with any specific event or class of events in the PLATO lesson. The access to PLATO provides a unique opportunity to study the psychophysiology of the instructional process. In addition, PLATO's extensive computing power coupled with its rich graphic display capabilities provide the user with unprecedented power to design complex experiments in human information processing.

It should be noted that an as yet unrealized benefit of the PLATO connection is that it provides users of the PLATO network direct access to our network. As any PLATO terminal can communicate with any other terminal, remotely located terminals can be provided with full access to the CPL's own network (albeit at speeds not exceeding 300 baud).

In a typical experiment the subject will be progressing through a PLATO drill and practice lesson. The sequence of PLATO material is intercepted by the GT40. This allows tighter control of the timing properties of the display. Moreover, the GT40 can initiate PLATO-related digitizing of EEG in relation to either stimulus or response events in the lesson. The data are displayed to the investigator and/or processed and stored for further analysis.

B.2.3.4 The Motor Performance Laboratory

A block diagram of this laboratory is shown in Figure 4. The central computer is a PDP 8/e with 16K of core, one disk and assorted peripherals. This laboratory is also equipped with a Hewlett Packard 3955 14 channel FM tape recorder. All



PDP-8 LAB

data are recorded on tape and digitized off-line on an IBM 1800 in the Psychology Department's computer facility. We plan to upgrade the system during 1977 to allow digital recording of the data. This will be done either by adding equipment to the PDP 8/e or by replacing the 8/e with another PDP 11.

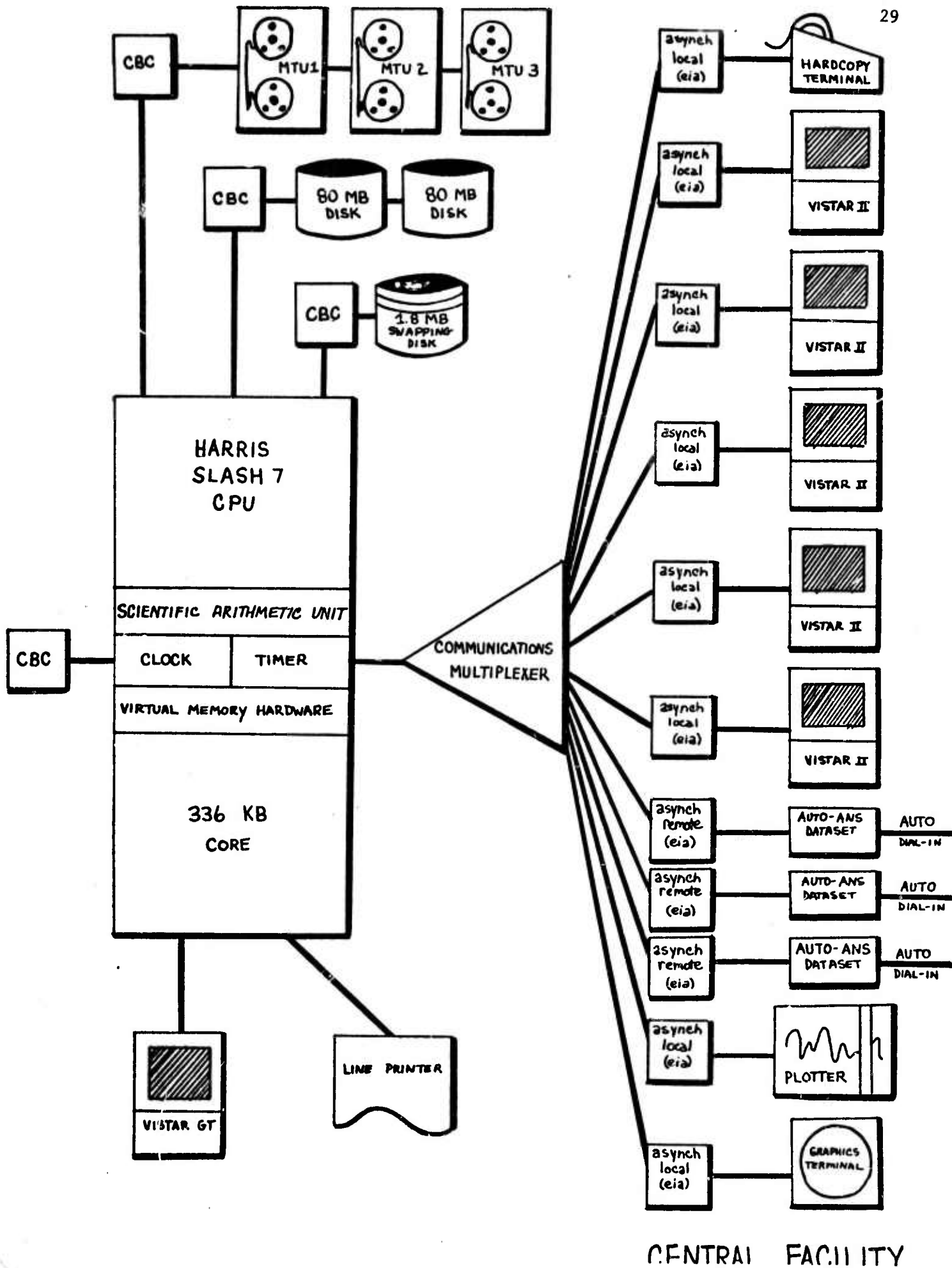
The lab is equipped with a 3 field Iconix T'scope, and the usual array of tones can be generated. A unique feature is a bimanual electronic dynamometer with which the force exerted by isometric movements of the subjects can be measured with considerable precision. The PDP 8/e is equipped with an interface to the PLATO terminal which allows the terminal's digital output to trigger actions by the computer. A limited range of PLATO related experiments can be conducted in the lab.

A typical experiment has the subjects squeeze one or the other of the dynamometers with the right or the left hand. Scalp potentials associated with the movements are digitized online by the PDP 8/e and the averages are displayed to the investigator. The EEG is continuously recorded on the FM tape in conjunction with event labeling pulses. The data are subsequently digitized and averaged on the IBM 1800 and the Harris computer.

B.2.4 The Harris Slash 7

The data acquired by the three laboratories is processed by this computer, a block diagram of which is shown in Figure 5. This 24 bit computer is equipped with three tape drives, two 80 MB disk drives and a 1.7 MB fixed head disk. Large data bases can be kept on the disks for analysis. The Harris can execute fairly elaborate statistical programs. We have, for example, implemented several programs of the BMD package, including the Principal Components Program (BMD08M) and the Stepwise Discriminant Analysis Program (BMD07M). Both are applied to data bases consisting of hundreds of 80-150 element vectors. The Harris can execute programs requiring up to 256 K words by utilizing its virtual memory feature. It can, in fact, execute several such programs in parallel.

Most of our work is done in FORTRAN, though the Harris supports BASIC and SNOBIL



as well as RPG. Its VULCAN operating system includes several important utilities, such as a SORT/MERGE package and a full accounting system. VULCAN has combined time-sharing and Batch capabilities, and the system can be accessed via 7 time sharing ports, three of which are available to remotely located investigators through Dial-in lines.

In addition to the BMD programs we have already implemented on the Harris a Time Series analysis package and a FORTRAN callable version of SOUPAC, the University of Illinois statistical analysis package. A variety of programs are also available for managing psychophysiological data bases. A measure of the system's power is the fact that it currently supports almost the entire data processing needs of the Cognitive Psychophysiology Laboratory. These needs were previously met by the Computer Services Office at Illinois and the CCN facility at UCLA. [Please note that while this section refers to the Harris Slash 7, we have as yet a Slash 4 only. This machine is substantially slower than the Slash 7. The Slash 7 will be delivered in the next couple of months.]

As soon as the link via DECNET is established between the Harris and the laboratory computers network, data could be streamed to the Harris during an experimental run. This will be done if, and when, data processing at a level exceeding the capacity of the PDP 11 will be required to determine the course of an experimental run. Thus for example, the Harris may be called upon to develop a discriminant function to be used during an experiment, to estimate the parameters of an adaptive filter, or to perform the computations required by the more complex displays.

In addition to its role as the prime number cruncher for CPL, the Harris will support a wide range of ancillary activities. We ordered an Imlac PDS-4 graphics terminal to allow interactive examination of the ERP waveforms. A Houston plotter is already on site. Other activities may range from manuscript preparation to bibliographic services.

SECTION C

THE USE OF EVENT-RELATED-POTENTIALS IN THE ENHANCEMENT
OF MAN-MACHINE SYSTEM PERFORMANCE

This section presents our current thinking on the manner in which a biocybernetic communication channel can be incorporated in a man-machine system to improve system performance.

The enhanced understanding of the ERP vocabulary together with the improved ability to read the vocabulary on single trials enables an accelerated exploration of the applications of the vocabulary in man-machine interactions. Two avenues of applications emerge from the present research. One related to the evaluation of operator's workload, task difficulty and spare capacity by using probe stimulus techniques and secondary task paradigms. This application is thoroughly discussed in Section C.1, together with a description of our preliminary experiment using a tracking task.

We also plan to pursue the enhancement of performance in multistimulus, multi-event time-varying situations, such as failure monitoring on multi-instrument panels, Air Traffic control situations, and C.A.I. lessons when students are presented with complex multielement displays. In all of these, due to temporal or other constraints, the operator attends selectively and processes actively only part of the available information for all practical purposes ignoring the rest. Stimulus selection is governed by a complex weighting function which is, for the great part, subjective and impossible to reconstruct from the final observed response. An index of selective attention that continuously indicates the events attended to can greatly enhance the efficiency of man-machine interaction. In failure detection and in air-traffic control situations such an index may be utilized to design improved warnings and information presentation algorithms. In other situations it may be used in computer aided decision making. In the C.A.I. environment it may be employed in the development of better material and student evaluation procedures, training schedules and branching techniques.

The results reviewed in other sections of this report support the idea that ERP can serve as such an index of selective attention. It was shown that ERP and in particular the P300 component is associated only with stimuli that were perceived as relevant and were actively processed. It was further shown that a complex (bi-modal or otherwise) situation can be decomposed so that the stimulus attended to can be identified. These results are also supported by earlier experiments from this lab. As we can identify these components on a trial to trial basis there is a strong indication they can be used in real environments. Finally, there are some indications that with the help of ERP measures we may be able to distinguish between failures of performance that originate from stimulus rather than from response selection problems. This is an important theoretical and practical distinction in the context of the complex command and control environment.

Section C.2 discusses in more detail the problems we shall address in the CAI environment and preliminary experimental plan.

C.1 Psychophysiological Measures in the Adaptive Man-Machine System

The remarkable developments in mini- and micro-computers is transforming the design of man-machine systems. The computer industry is producing smaller, faster and more economical computers. It is, therefore, increasingly easier to incorporate computers as control components in man-machine systems with striking effects on the flexibility of the systems. Most notable is the increasing prevalence of adaptive systems. In these the computer can affect the nature of the man-machine interaction by implementing dynamically, an optimizing algorithm. System behavior can be adjusted to the continually changing states of the operator, the environment and to the interaction between the two. This flexibility depends on an exchange of information between the operator and the machine. Within the framework of a computer based system it is possible to conceive of novel channels of communication to supplement conventional display and control interfaces. This report describes a program, which is one of several Biocybernetic programs supported by ARPA's Cybernetic Technology Office, which

seeks to develop such a communication channel utilizing information which can be derived from brain-waves.

The environment for which we developed these channels is exemplified by the hypothetical high performance aircraft with on-board computer facilities represented in Figure 1. The conventional Display, Pilot, Control and Plant components are supplemented by various performance aids which can be implemented or adjusted on-line. These may consist of the addition or removal of predictive display information, an alteration of the Control or Plant dynamics along various axes or perhaps the assumption of control of certain tasks normally performed by the operator. In order that these adaptive decisions be made intelligently by the on-board aiding center, a managing computer or Decision Center shown in Figure 1 must be well informed. The information it requires includes obviously characteristics of the mission, the status of other aircraft, vehicular disturbances and ground controlled inputs. Additionally, it would be extremely useful to the Decision Center to have estimates of two important aspects of the operator's attentional state: what information he is processing or ignoring at any time (selective attention), and his overall level of workload or involvement with on-going tasks. Operator workload in this sense is often conceptualized as a variable that is reciprocally related to the amount of residual attention available to deal with unexpected environmental contingencies (1).

Various performance measures are traditionally used to index attention and workload. These have been found to provide adequate indices of both aspects of the attentional state. For example, in a multi-display selective attention task, the allocation of attention between sources of discrete stimuli has been revealed by response latency (2,3) or accuracy (4). Attention allocation to continuous tasks has been successfully identified through changes in tracking gain (2,4), information transmitted (4), time delay (5), holds in the tracking output (6,7), remnant or observation noise (8,9), or by more complex coefficients of a linear discrete time series model (10).

Operator workload or residual attention has often been measured by the "secondary

FUNCTIONAL RELATIONSHIP AMONG ELEMENTS IN THE SYSTEM

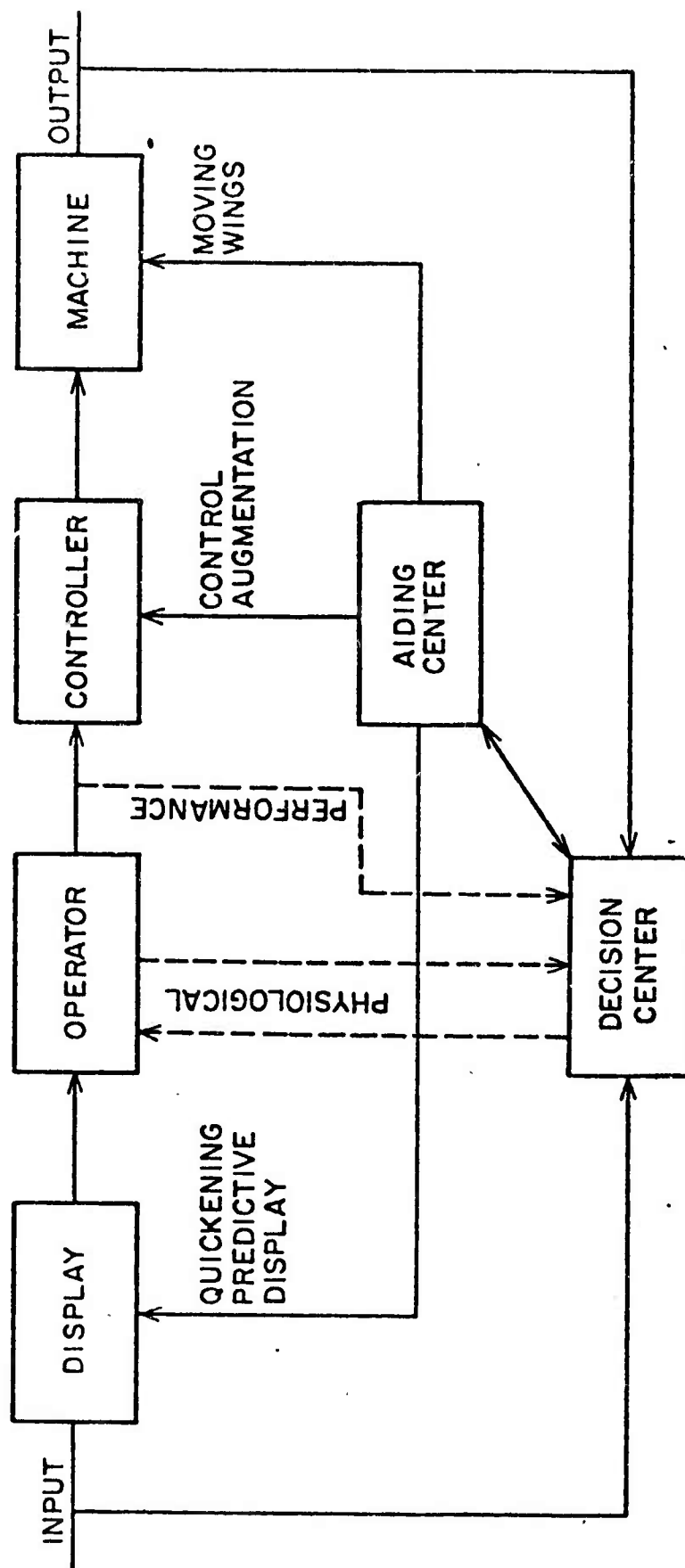


Figure 1

task loading" technique (11). The operator is presumed to possess some limited quantity of processing resources which can be distributed among various tasks. As a primary task is made more difficult--its workload demand increased--a greater quantity of the limited resource is required to maintain criterion performance, and conversely a lesser amount remains to perform the secondary task. As a consequence, secondary task performance decreases, serving as an index of primary task difficulty. Such techniques have proven reliable in comparing different display or control configurations (12), or in validating subjective estimates of control task difficulty (13).

While performance measures do serve adequately as indices of selective attention, their use is necessarily restricted to tasks in which overt responses are produced. Thus they are inappropriate for a class of tasks that are becoming critically important in modern system control: passive monitoring during which few overt responses are emitted by the operator. To assess the allocation of attention during a monitoring task, periodic probe events must be inserted in the environment and an overt (detection) response to the probes required. Such probes are of necessity disruptive to ongoing performance. The difficulties encountered by an on-line assessment of workload through secondary task loading are more severe. The secondary task performance may well disrupt performance on the primary task with possibly critical consequences. It may also "saturate" the residual attention that it was designed to assess.

Even in situations where the above restrictions are not encountered (for example divided attention between two information transmission tasks), a further limitation upon the usefulness of performance measures is presented by the inherent response variability which precludes reliable estimates of attention-sensitive parameters from a single observation. Thus assessment of any or all of the performance measures described above must involve a number of behavioral observations taken over time, a requirement which further limits the usefulness of these measures in closing an on-line adaptive loop such as that shown in Figure 1.

The shortcomings of performance measures point to an urgent need for additional

sources of information which can either supplement or, as in the monitoring and workload-measurement situations described above, replace the performance measures in providing information to the Decision Center. It is for this reason that we have initiated an investigation to determine if psychophysiological measures can serve as indices of human information processing characteristics. Psychophysiological measures have two important properties that counteract the drawbacks of performance variables pointed out above. (These advantages are, of course, purchased at the cost of increased complexity in measurement. The cost effectiveness of these procedures is a matter for future research and will not be discussed here.) It is reasonable to assume that the inherent random noise sources which perturb, or contribute to the variability of psychophysiological measures are relatively uncorrelated with the sources or performance variability. Assuming an independence of the noise sources, the information provided jointly by both signals in any given observation period should be of greater reliability than the information provided by either source alone. In other words the time required for a Decision Center to obtain an estimate of the subject's internal state at a given level of reliability will be reduced when estimates are based upon joint measures.

The second advantageous feature of psychophysiological measures is that, with proper instrumentation, they may be assessed in a manner that is less disruptive to ongoing performance than the monitoring "probes" or the secondary tasks discussed above. One example of the potential usefulness of such measures has been provided by another Biocybernetics project in which Beatty (14) has demonstrated the utility of pupil diameter as a measure of the operator's cognitive processing load. Our own efforts focus on the scalp recorded event-related-potential (ERP) as a source which may provide useful information concerning the operators cognitive state.

C.2 The Event-Related-Potential

The ERP is a transient voltage change in the brain which is elicited by any discrete event, and which may be recorded by surface electrodes attached to the scalp.

Superimposed on the ongoing EEG, the ERP extends for at least 500 msec. and is characterized by a series of distinct positive and negative-going peaks with characteristic latencies following the stimulus (15,16). The amplitude of the different peaks appears to be sensitive to physical and informational characteristics of the stimulus. The multivariate nature of the ERP provided by the separate peaks reinforces its potential value in providing considerable information to an on-board computer.

Although normally the ERP to a single stimulus is masked by the on-going EEG voltage, rendering it difficult to identify from a visual record, multitrial averaging techniques can serve to cancel the noise contribution and provide an estimated ERP associated with an event. Alternatively, and of critical importance for on-line assessment of behavior, a wide variety of techniques are being developed and implemented as a part of this project which will enable successful identification and classification of the characteristics of an ERP on a single trial (17,18). Such techniques include frequency domain filtering of EEG activity, iterative time domain adjustment to reveal peaks (19) or application of linear discriminant analysis (20).

Although the success of ERPs as indicants of attention in a complex cockpit-like environment has not been established, there is nevertheless strong experimental evidence that components of the waveform are sensitive to attentional manipulations. Thus for example, Donchin and Cohen (21) have found that the amplitude of the late positive peak of the waveform (P300) reflects the allocation of attention to each of the elements in a two element visual display. This finding has been replicated in the auditory modality (22,23). Earlier components of the waveform have also been found to be enhanced by focussed attention (24,25). Clearly then, the evoked potential does reflect all-or-none discrete shifts in attention as defined by the relevance or non-relevance of an information source.

There is much less validation in the literature of the ability of the ERP measures to distinguish between levels of workload or attention on a continuous or graded basis in a manner which has been established with performance variables (e.g., 2,5). In a study in which ERPs were recorded to stimuli in a two-channel signal detection task,

LaFayette, Dinand and Gentil (26) were able to observe changes in the early positive and negative components of the ERP as the stimuli were made more or less relevant by instructional manipulations. In a second study, they found reliable changes in the early components of the ERP to detected tones as the workload of a secondary cognitive reasoning task was manipulated.

C.3 Preliminary Experimentation

We are currently investigating the capability of ERP measures to reflect the subject's information processing characteristics in an environment that simulates more closely the control and monitoring tasks confronted by the pilot. Our basic experimental approach is to record ERPs to probe auditory or visual stimuli. These probes are either irrelevant to the tasks performed (and may therefore be ignored by the subjects), or require only a minimum amount of cognitive processing, thus avoiding any disruption or primary task performance. In a selective attention/monitoring paradigm, the probe stimulus may occur along one of the relevant channels, displays or information sources to determine if the elicited ERP will reflect the extent to which that source is being processed. The stimulus attribute of the probe will however be different from the attributes of the channel that is relevant to the monitoring task. That is, if the subject is monitoring a visual channel for a spatially defined event, the probe will involve an intensity-change. Alternatively, in a divided attention processing task, the ERP-eliciting stimuli can be the same stimuli as those that are processed and responded to in the performance of the tasks. Finally, in a workload manipulation paradigm, the probes are presented along channels that are totally irrelevant to the primary task performed, in order to determine if the elicited ERP's will reflect the residual attention available from that task as its workload is manipulated.

We have investigated ERP's and residual attention in a pilot experiment in which six subjects performed a two-dimensional pursuit tracking task with dynamics

of the form

$$Y = \frac{K_1 + K_2 S}{S}$$

on both axes. Twelve 3-minute practice trials were first presented to bring the subjects to a stable level of performance via adaptive techniques with forcing function cutoff frequency employed as the adaptive variable.

ERP's were next recorded in two workload manipulation sessions. The probes consisted of a Bernoulli series of rare and frequent tones differing in pitch. The two sessions differed from each other according to whether the probe stimuli were ignored or processed. "Processing" involved maintaining an internal count of the number of rare stimuli that occurred during a trial (see Figure 2).

Within each session, workload was manipulated by two different methods (Figure 3). First, the forcing function bandwidth was increased and decreased by 30% from the asymptotic level, achieved by each subject in the adaptive practice session. This generated 3 different levels of objective task difficulty. Then, based upon the performance of each subject in the intermediate and high bandwidth conditions (moderate and large error respectively), two target diameters were selected, equal in value to the RMS error measured for each subject in those two conditions. A third, larger diameter was also selected of proportionately greater size. In this manner the manipulation of target diameter, or required error tolerance was "calibrated" for each subject according to his sensitivity to the bandwidth manipulations, the object of this calibration being to obtain equivalent manipulations of subjective performance demands across all subjects. Tracking under the three target sizes was performed at the constant intermediate bandwidth level. It was therefore assumed that progressively more residual attention would be made available from the tracking task as the error tolerance (and obtained error) was increased.

The two particular workload manipulations employed may be placed in context by assuming that the attentional demands or subjective difficulty of a task is a joint function of its objective difficulty (e.g., task characteristics such as input bandwidth or dynamics), and the performance level required (in the present case, specified by the target diameter). What we have done then is to manipulate each of these dimensions of difficulty separately, while holding the other constant.

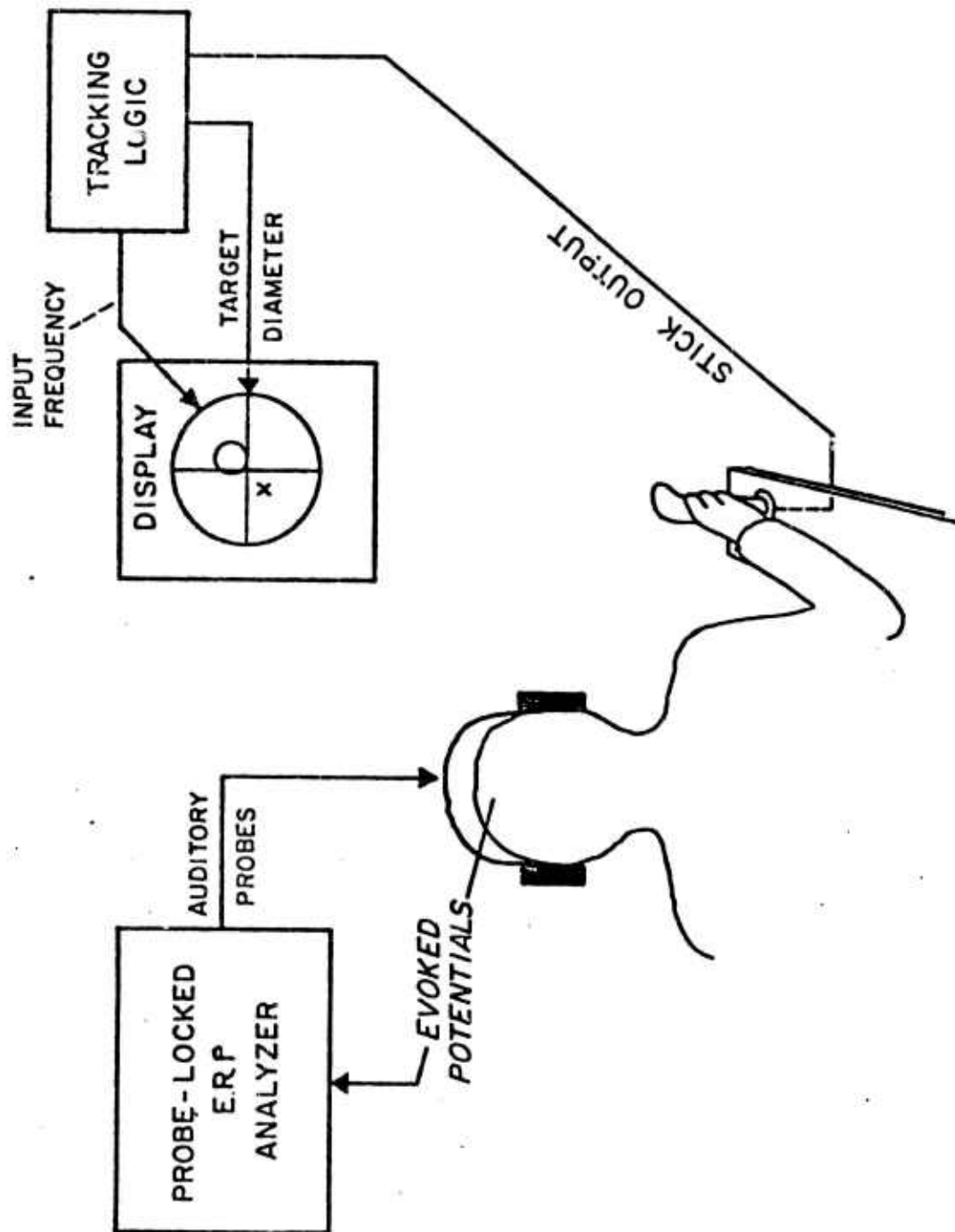


Figure 2

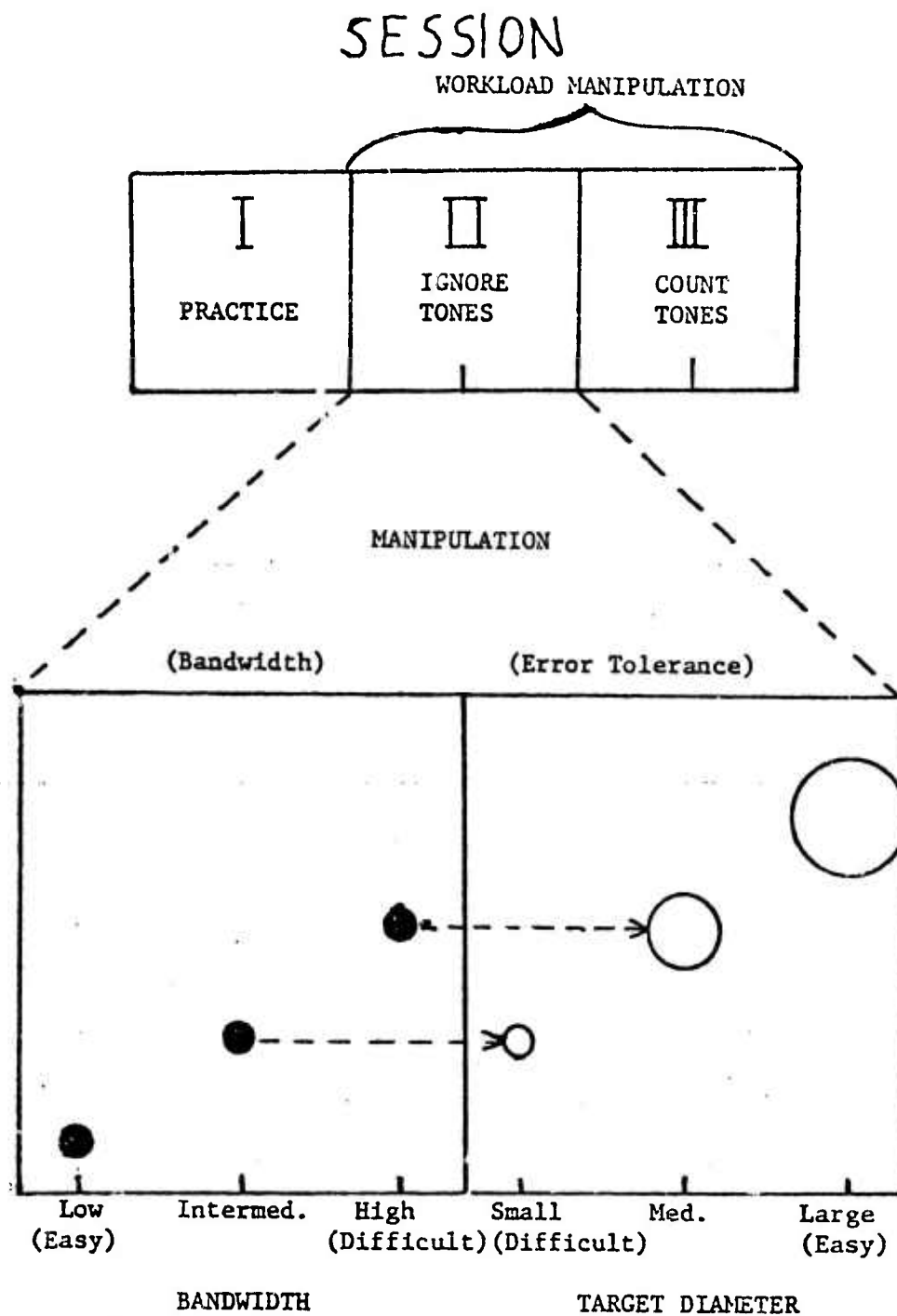


Figure 3
Experimental Design

The logic of the tracking task, probe signal presentation and ERP recording was controlled by a PDP 11/40 computer (27). ERP's recorded from 3 electrode sites were amplified and were displayed on-line via a GT-44 graphics display terminal. The data was also recorded on digital tape for later off-line analysis and plotting by a Harris computer.

The preliminary data thus far collected has indicated that stable ERP waveforms can in fact be elicited by probes under the high levels of primary task workload required in the experiment. At this writing the data are being analyzed and it is already clear that there is a substantial degree of individual differences in the shape and temporal characteristics of the waveforms. These may well be related to different strategies that subjects adopt in performing their assigned tasks, and these strategies will be investigated through future analysis of the tracking data in the time and frequency domain. It appears however that there is some consistency within the waveforms of a given subject. In this case the between-subject variability presents no serious difficulty and may well prove useful in assessing individual differences in performance. In a sense, calibrating an ERP analyzer to the physiological response characteristics of an individual operator imposes no greater engineering demands than custom designing the helmet or flight suit to his anthropometric characteristics.

At this point, the state of our research is too preliminary to draw firm conclusions concerning the effects of attentional manipulations upon the event-related-potentials. However, given the projected importance of nondisruptive measures, and the established sensitivity of such measures to certain attentional variations in the laboratory, we are sufficiently encouraged to pursue the direction of experimentation outlined above.

References

1. Kahneman, D. Attention and Effort. New York: Prentice Hall, 1973.
2. Gopher, D. and Wickens, C. Strategies and attention allocation in dual-task performance. Proceedings 11th Annual Conference on Manual Control. NASA

- TMX-62, 464. Washington, D.C.: U.S. Government Printing Office, 1976.
3. Ephrath, A. Detection of system failure in multi-axis tasks. Proceedings 11th Annual Conference on Manual Control. NASA TMX-62, 464. Washington, D.C.: U.S. Government Printing Office, 1976.
 4. Baty, D. L. Human transinformation rates during one-to-four axis tracking. Proceedings 7th Annual Conference on Manual Control. NASA, SP-281. Washington, D.C.: U.S. Government Printing Office, 1972.
 5. Jex, H. Two applications of a critical-instability task to secondary work load research. IEEE Transactions on Human Factors in Electronics, 1967, HFE-8, 279-282.
 6. Onstott, C. D. Task interference in multi-axis aircraft stabilization. Proceedings 12th Annual Conference on Manual Control. Urbana, Illinois, May, 1976.
 7. Cliffe, R. C. The effects of attention sharing in a dynamic dual-task environment. Proceedings 7th Annual Conference on Manual Control. NASA SP-281. Washington, D.C.: U.S. Government Printing Office, 1972.
 8. Levison, W. H., Elkind, J. I., and Ward, S. L. Studies of Multivariate Manual Control Systems: A Model for Task Interference (NASA CR-1746) Bolt Beranek & Newman, May 1971.
 9. Wickens, C. D. The effects of divided attention on information processing in manual tracking. Journal of Experimental Psychology: Human Perception and Performance, 1976, 2: 1-13.
 10. Engstrom, K. D. and Rouse, W. B. Telling a computer how a human has allocated his attention between control and monitoring tasks. Proceedings 12th Annual Conference on Manual Control. Urbana, Illinois, May, 1976.
 11. Rolfe, J. M. The secondary task as a measure of mental load. In W. T. Singleton, R. S. Easterby, and D. E. Whitfield (Eds.), Measurement of Man at Work. London: Taylor & Francis, 1971.
 12. Krauss, E. F. and Roscoe, S. N. Reorganization of airplane manual control flight

- dynamics. In W. B. Knowles, M. S. Sanders and F. A. Muckler (Eds.), Proceedings 16th Annual Meeting of the Human Factors Society. Santa Monica, California: October, 1972.
13. Clement, W., McRuer, D., and Klein, R. Application of New Pilot Workload Measure to Manual Control Display Design. System Technology, Inc. Paper No. 133, April 1973.
 14. Beatty, J. Pupilometric measurement of cognitive workload in complex man/machine systems. Proceedings 12th Annual Conference on Manual Control. Urbana, Illinois, May 1976.
 15. Donchin, E. Brain electrical correlates of pattern recognition. In G. F. Inbar (Ed.), Signal Analysis and Pattern Recognition in Biomedical Engineering. New York: John Wiley, 1975. Pp. 199-218.
 16. Regan, D. Evoked Potentials in Psychology, Sensory Physiology and Clinical Medicine. London: Chapman and Hall, Ltd., 1972.
 17. Donchin, E. and Herning, R. I. A simulation study of the efficacy of stepwise discriminant analysis in the detection and comparison of event related potentials. Electroencephalography and Clinical Neurophysiology, 1975, 38: 51-68.
 18. Squires, K. C. and Donchin, E. Beyond averaging: The use of discriminant functions to recognize event related potentials elicited by single auditory stimuli. Electroencephalography and Clinical Neurophysiology, 1976, In press.
 19. Woody, C. D. Characterization of an adaptive filter for the analysis of variable latency neuro-electric signals. Medical and Biological Engineering, 1967, 5: 539-553.
 20. Donchin, E. Discriminant analysis in averaged evoked response studies: The study of single trial data. Electroencephalography and Clinical Neurophysiology, 1969, 27: 311-314.
 21. Donchin, E. and Cohen, L. Average evoked potentials and intramodality selective attention. Electroencephalography and Clinical Neurophysiology, 1967, 22: 537-546.

22. Smith, D. B., Donchin, E., Cohen, L., and Starr, A. Auditory averaged evoked potentials in man during selective binaural listening. Electroencephalography and Clinical Neurophysiology, 1970, 28: 146-152.
23. Squires, K., Donchin, E., Herning, R., and McCarthy, G. On the influence of task relevance and stimulus probability on ERP components. Electroencephalography and Clinical Neurophysiology, 1976, In press.
24. Schwent, V. and Hillyard, S. A. Auditory evoked potentials during multi-channel selective listening role of pitch and localization cues. Electroencephalography and Clinical Neurophysiology, 1975, 38: 131-138.
25. Wilkinson, R. T. and Lee, M. V. Auditory evoked potentials and selective attention. Electroencephalography and Clinical Neurophysiology, 1972, 33: 411-418.
26. LaFayette, Dinand and Gentil. Average evoked potentials in relation to attitude, mental load, and intelligence. In W. T. Singleton, R. S. Easterby, and D. E. Whitfield (Eds.), Measurement of Man at Work. London: Taylor & Francis, 1971.
27. Donchin, E. and Heffley, E. Minicomputers in the signal-averaging laboratory. American Psychologist, 1975, 30: 299-312.

C.4 Biocybernetic Feedback in a CAI Environment

Computer Assisted Instruction (CAI) was to provide an individualized learning environment which could improve both the rate and the level of learning. Early enthusiasm has waned somewhat as the great expectations were not fulfilled (Watson, 1972; Jamison, Suppes, and Wells, 1974). A re-evaluation of the underlying initial assumptions has led to a diminution of dependence on the analytic, theory based approach to the design of CAI materials. Today the development of instructional materials on the PLATO CAI system generally proceeds according to a tistic and empirical methods (Bunderson and Faust, 1976). Often used together, the artistic approach relies on the early intuitions of the instructional designer to assure

creation of quality material, and the empirical approach uses a cycle of construction, testing, and revision in order to produce valid instruction. Both exploit and explore the interactive nature of the medium, emphasizing its ability to individualize the questioning, feedback, and routing process based on inputs from the student (Avner, 1976; Steinberg, 1975; Nievergelt, 1975).

Besides the practical goals of producing quality instruction, the implicit goal of this exploration is to discover new theories of interactive education. We share their goal in our attempt to add biocybernetic feedback to the CAI environment.

C.4.1 Problem

The acronyms PLATO and TUTOR (the language used on the PLATO system) both imply the providing of a dialogue context between the student and the computer which can offer the rich interaction that exists between a human tutor and student. Both human and computer tutors will always have some difficulty communicating; however, the human tutor currently has both a much greater capacity for understanding the student than the computer does and can achieve a quantitatively better information exchange ratio than the computer can. CAI systems have traditionally been handicapped by their inability to disambiguate natural language inputs. Both the literal and connotative meanings of words change with even a slight change in context. The TUTOR language addresses this problem by providing a uniquely rich selection of context establishing procedures for evaluating student responses (Tenczar and Golden, 1972; Sherwood, 1975). Nevertheless, understanding even simple student inputs still remains a time consuming process for the developer, and results in oversized instructional programs.

The other disadvantage of CAI is that its information exchange rate is still heavily biased in favor of computer to student interactions. Sherwood and Stifle (1975) have reported that the information transfer rate for a typical PLATO lesson is approximately 100:1 in favor of the computer. Because of the overhead for analyzing natural language inputs, it is unlikely that quantitatively increasing student initiated information without a qualitative improvement would be all that beneficial.

In an attempt to provide such qualitatively different information, the PLATO system has expanded the communication modes available to the student by providing typing, touching, and a variety of peripheral devices such as a joy stick, music box, and passenger car simulator (Wood, 1975; Trollip and Ortoney, 1976; Peters and Colwell, 1975; Parker and Voss, 1975).

We will attempt to improve on this "bottleneck" for student-initiated communications by providing a biocybernetic feedback channel which can transmit information to PLATO about the attention, expectation, and level of understanding indicated by the student along with traditional communications. Such internal "state" indicators which can be consciously tapped are regularly used for self-instruction, and the non-verbal communication channel used by a human tutor receives this kind of information through external signs exhibited by the student, such as changes in physical posture and voice quality.

Despite the expanded environment and four years of experimentation, PLATO instruction has yet to demonstrate that it can more than equal the accomplishments of traditional classroom instruction. The information exchange ratio predicts that PLATO should teach about as well as a classroom teacher. Results of attitude questionnaires indicate that students enjoy, and often prefer, using PLATO; but it is obvious to them that CAI has not yet "arrived." They have too often been bored or frustrated by simplistic and incomprehensible questioning sequences which are unfortunately still typical of much instruction. The addition of biocybernetic feedback to the PLATO environment could help move PLATO toward its goal of individualizing learning.

A similar attempt to tap the student's understanding of his/her learning state directly has been to place the learner in control of the instruction process (Anastasio and Morgan, 1972; O'Neal, 1973; Pask, 1976). CAI systems such as TICCIT (Bunderson, 1973) which use this approach place the computer in the role of an augmented information retrieval system, and require that the student make operational decisions. The theory behind the approach asserts that the student will make more competent selection

decisions than a computer based on personal, intuitive knowledge about the learning state; and will gradually develop superior learning strategies. Recent experimentation on the PLATO system, however, indicates that students select their initial learning strategy from cues such as the index arrangement, and do not change this strategy with experience (Elliott, 1976; Lahey, 1976). Dwyer (1975) among others has discussed the need for careful guidance by a human teacher or a computer in order to teach learning strategies. The student state information which can be provided by biocybernetic feedback is thus needed for both goals in the CAI environment, and cannot be bypassed by placing the learner in control.

C.4.2 Research

Our expectations are that we can eventually use biocybernetic feedback to improve CAI on all levels: student-computer communication, formative evaluation of existing material, teaching learning strategies, and the development of theories of interactive instruction. Our initial efforts will emphasize the augmentation of student-computer communication in four areas, 1) determining mastery of drill items (rote learning, simple memorization tasks), 2) deciding when it is necessary to question during long textual presentations, 3) evaluating the instructional success of specific questions, and 4) applying the results of applied tracking research involving measures of effort and attention measurement to dynamic training simulations.

C.4.2.1 Drill

This investigation will explore the relationship between ERP measures, performance, reaction times, and behaviorally indicated confidence of mastery, with the aim of using the student's perception and evaluation of the learning task to improve the rate of learning. The presence of the P300 component of event-related potentials has been repeatedly correlated with variables of uncertainty, expectancy, and confidence (Squires et al., 1976; Tueting, 1976). By using this component as an on-line source of biocybernetic feedback, we hope to obtain information about the student's confidence in the correctness of a given response.

The confidence indication will be used to supplement a traditional decision

model for drill instruction, such as the one used by Suppes (Atkinson, 1972; Suppes and Morningstar, 1972) to teach arithmetic on a CAI system. This model describes the state of each item in a drill list as being either not learned, partially learned, or learned, depending on how many sequentially correct responses have been given for the item. A criterion level is defined for the set which guarantees at least 90% probability of mastery. With the student response as the only information source, such algorithms guarantee learning by the "overkill" method. The addition of biocybernetic information could optimize the application of this algorithm through dynamic adjustment of the criterion level of each item. Thus the program could abort the need for overt responding, or reduce the criterion level if confidence is high; and raise the criterion level if the uncertainty reading contradicts performance measures.

C.4.2.2 When to Question

By using ERP measures to adapt the frequency of questioning and speed of presentation of long prose passages, we will attempt to improve both the rate and level of concept learning. Anderson and Biddle (1976) have reviewed the research on inserted questions, concluding that by forcing the student to attend to more than the surface structure of the material, questions are highly effective in insuring both immediate attention and improved retention. But questioning for this purpose is disfunctional as long as the student is properly attending to the reading material. We will attempt to continuously monitor the attention and periodically measure the uncertainty levels of a student reading an extended prose passage. A deterioration in the attention level of the student will be used as a cue for initiating a question, recommending a break, or skipping ahead to more difficult material. High uncertainty accompanying the reading of summative passages, will be used as a cue for inserting a question and/or additional explanations to insure complete learning of the material. The results of this computer controlled systems should be to allow the student to read undisturbed as long as s/he is attending effectively, and to use questions only when they are needed.

C.4.2.3 Formative Evaluation of Questions

A second area of interest in prose learning is in evaluating the effectiveness of a specific question in measuring a student's understanding. Carroll (1972) has discussed the differential processing required by recall and recognition questioning modes, and Markle (1973) has enumerated some of the problems which can remain in lessons which have been through the empirical revision process; including questions which test superficial understanding are ambiguous, or test question-answer ability. We will evaluate the success of questions in operational CAI lessons by comparing the level of processing evoked by a question with the confidence that a student indicates in the correctness of his/her response, the specified response, and surprise at subsequent feedback. A lack of processing indicated by a large number of students will be defined as an unsatisfactory/unnecessary question whether student responses were correct or incorrect. An indication of confidence accompanying an incorrect answer will indicate an ambiguous or misleading question. Thus, we could unobtrusively gather new, useful information about the importance and function of inserted questions.

C.4.2.4 Improving Communication in Dynamic Simulations

The simulation and simulation/gaming modes of instruction have been the most consistently popular and successful lessons on the PLATO system (Hyatt, Eades, and Tenzar, 1972; Grimes, Burke, North, and Friedman, 1974; Smith, Chesquire, and Avner, 1974; Neal, 1974). Because of their well defined context, explicit rules, limited moves, non-verbal modes of interaction, and the mathematical nature of the models, the problems of disambiguating student responses are minimized. Evaluation of student success is based on the efficiency in manipulating the model toward well-defined goals. Despite their general success as training tools, simulations to date are still very limited in their adaptive capabilities, adjusting parameters in real time to correspond with students' performance and rate of progress. These limitations seem to result primarily from the inability to obtain, with traditional measures, high quality information about the student quickly enough to make effective adaptive

decisions. The techniques developed in our applied tracking research program will be applied to the CAI instructional environment. Research measures of attention, effort, and processing levels will be used to provide performance feedback to the student, and to adapt the parameters of the simulation to the competency of the student.

For example, the driving simulation described by Parker and Voss (1975) provides a continuous experience in which a student uses wheel and pedal controls to demonstrate understanding of the driving task. Hazards, road signs, and other changes in the driving environment can be selectively included in the display. By measuring the attention that a student gives to a new stimuli such as a caution sign, and comparing it to performance when the hazard actually appears, we may be able to identify the foresight that a student had into the driving context, and use this information to assist in the evaluation of performance and the selection of future stimuli. The degree of attention required for correct performance will also allow us to predict the students' mastery over a specific context. So with the addition of biocybernetic feedback the simulation should be able to adapt to the competency of the student dynamically and efficiently.

References

- Anastasio, E. and Morgan, J. Factors Inhibiting the Use of Computers in Instruction. EDUCOM, 1972.
- Anderson, R. C. and Biddle, W. B. On asking people questions about what they are reading. Psychology of Learning and Motivation, 1975, Vol. 9, pp. 89-132.
- Atkinson, R. C. Ingredients for a theory of instruction. American Psychologist, October, 1972, 27: 921-931.
- Avner, R. A. CAI Design as an Evolutionary Process. Symposium on "CAI Design as an Evolutionary Process," Annual Meeting of American Educational Research Association, Washington, D.C., 1975.

- Bunderson, V. The TICCIT Project: Design Strategy for Educational Innovation.
ICUE Technical Report No. 4. Provo, Utah: Institute for Computer Uses in Education, Brigham Young University, 1973.
- Bunderson, C. Victor and Faust, Gerald W., Programmed and Computer-Assisted Instruction, Chapter 3 of National Society for the Study of Education Yearbook, University of Chicago Press, Chicago, 1976.
- Carroll, J. B. Defining language comprehension: Some speculations. In Carroll, J. B. and Freedle (Eds.) Language Comprehension and the Acquisition of Knowledge. Washington, D. C.: V.H. Winston & Sons, 1972.
- Dwyer, T. A. Heuristic strategies for using computers to enrich education. International Journal of Man-Machine Studies, 1974, 66: 1-16.
- Elliott, P. H. An exploratory study of adult learning styles. Paper presented at the American Educational Research Association Annual Meeting, San Francisco, 1976.
- Grimes, G. M., Burke, T. J., North, L., and Friedman, J. Diagnosing simulated clinical cases using a computer-based education system. Journal of Veterinary Medical Education, 1974, 1(2).
- Hyatt, G., Eades, D., and Tenczar, P. Computer-based education in biology. BioScience, July, 1972, 22(7): 401-409.
- Jamison, D., Duppes, F., and Wells, S. The effectiveness of alternative media: A Survey. Review of Educational Research, 1974, 44(1): 1-67.
- Lahey, G. F. Learning control of lesson strategy: Some tentative results. Paper presented at the American Educational Research Association Annual Meeting, San Francisco, 1976.
- Markle, D. G. In which it is demonstrated that a program that works may well be worthless. Improving Human Performance, Fall 1973, 3: 161-164.
- Neal, J. P. Electronic laboratory instruction using the CGE-PLATO laboratory station. MTC Report No. 5, CERL, Urbana, Illinois, 1974.

- Nievergelt, J. Interactive systems for education -- The new look of CAI.
Invited paper presented at the IFIP 2nd World Conference on Computer Education.
Marseilles, France, 1975.
- O'Neal, F. Learner Control of Instruction: Requirements and Potentials. ICUE Technical Report #2, Institute for Computer Uses in Education, Brigham Young University, Provo, Utah, 1973.
- Parker, L. and Voss, J. PLATO and Driver Services. CERL, University of Illinois, Urbana, Illinois, 1975.
- Pask, G. Anti-hodmanship: A report on the state and prospects of CAI. Programmed Learning and Educational Technology, 1972, 9(5): 235-244.
- Peters, G. and Colwell, R. J. Computer-Assisted Instruction in Music at the University of Illinois. Computer-Based Educational Research Laboratory, Urbana, Illinois, 1975.
- Sherwood, B. A. The TUTOR Language. Computer-Based Education Research Laboratory, University of Illinois, Urbana, Illinois, 1975.
- Sherwood, B. A. and Stifle, J. The PLATO IV Communication System. CERL Report X-44, 1975.
- Smith, S. G., Chexquiere, J. R., and Avner, R. A. The use of computers in the teaching of chemistry -- Evaluation of lesson effectiveness. Journal of Chemistry Education, 1974, 51(4): 243-244.
- Squires, K. C., Wickens, C., Squires, N. K., and Donchin, E. The effect of stimulus sequence on the waveform of the cortical, event-related potential. Science, 1976.
- Steinberg, E. R. The Evolutionary Development of CAI Courseware. Symposium on CAI Design as an Evolutionary Process. Annual Meeting of American Educational Research Association, Washington, D.C., 1975.
- Suppes, P. and Morningstar, M. Computer-Assisted Instruction at Stanford, 1966-1968. New York: Academic Press, 1972.
- Tenczar, P. and Golden, W. Spelling, Word and Concept Recognition. CERL Report X-35, 1972.

Trollip, S. and Ortoney, A. Real-time simulation in computer assisted instruction.

Science Instruction, In press.

Tueting, P. Event related potentials: Cognitive events and information processing.

EPIC IV, 1976. in press.

Watson, P. Using the Computer in Education. E. Tech. Publications, Englewood Cliffs, New Jersey, 1972.

Wood, N. The PLATO System. Computer-Based Education Research Laboratory, Urbana, Illinois, 1975.

SECTION D
EXPERIMENTAL REPORTS

In this section we include copies of several reports which describe in detail experimental and theoretical work conducted with the support of this program.

The reports are briefly described here.

- D.1 Squires, K. C., Wickens, C., Squires, N. K., and Donchin, E. The effect of stimulus sequence on the waveform of the cortical, event-related potential. Science, 1976, in press.

Describes our discovery of the effects of sequential dependencies on P300 amplitude and presents the Expectancy model.

- D.2 Squires, N. K., Donchin, E., Squires, K. C., and Grossberg, S. Bisensory stimulation: Inferring decision-related processes from the P300 component. Journal of Experimental Psychology, 1976, in press.

A demonstration that the P300 can be used to infer which of two channels of information are processed by a subject. The data also reinforce our notion that P300 represents stimulus evaluation rather than response selection processes.

- D.3 McCarthy, G., and Donchin, E. The effects of temporal and event uncertainty in determining the waveforms of the auditory event related potential (ERP). Submitted to Psychophysiology.

A demonstration that P300 is enhanced by the resolution of event uncertainty rather than by temporal uncertainty.

- D.4 Kutas, M., and Donchin, E. Variations in the latency of $\overline{P300}$ as a function of variations in semantic categorizations. In D. Otto (Ed.), Proceedings of EPIC IV. Washington, D.C.: Government Printing Office, 1976, in press.

Describes the first experiment in which we used the PLATO terminal.

Demonstrates that P300 varies with the complexity of a categorization response and indicates that it is elicited at the termination of the processing activity.

- D.5 Donchin, E., Kutas, M., and McCarthy, G. Electro cortical indices of hemispheric utilization. In S. Harnad et al. (Eds.), Lateralization in the Nervous System. New York: Academic Press, 1976, in press.

A critical review of research on hemispheric lateralization and a description of some of our experiments in this field.

- D.6 Squires, K. C., Donchin, E., Herning, R. I., and McCarthy, G. On the influence of task relevance and stimulus probability on event-related-potential components. Electroencephalography and Clinical Neurophysiology, 1976, 41, in press.

A survey of the endogenous components of the auditory ERP in a counting paradigm.

- D.7 Squires, K. C., and Donchin, E. Beyond averaging: The use of discriminant functions to recognize event related potentials elicited by single auditory stimuli. Electroencephalography and Clinical Neurophysiology, 1976, 41, in press.

The efficacy of stepwise discriminant analysis demonstrated.

Reports

The Effect of Stimulus Sequence on the Waveform of the Cortical Event-Related Potential

Abstract. The waveform of the cortical event-related potential is extremely sensitive to variations in the sequence of stimuli preceding the eliciting event. The waveform changes were manifested primarily in the amplitudes of the negative component of the potential that peaked at 200 milliseconds, the positive component that peaked at 300 milliseconds, and slow-wave components. A quantitative model was developed relating the waveform changes to changes in event expectancy. Expectancy is assumed to depend on a decaying memory for events within the prior sequence, the specific structure of the sequence, and the global probability of event occurrence. For stimuli relevant to the task, the less expected the stimulus the larger the amplitudes of late components of the event-related potentials.

The cortical event-related potential (ERP) associated with the rare outcomes of Bernoulli trials that are relevant to a task is different from that associated with the frequent outcomes (1-3). If, for example, a subject is instructed to count the occurrences of a few low-pitched tones embedded in a series of high-pitched tones, the low-pitched tones elicit ERP's characterized by a large negative component peaking at 200 msec (N200), a large positive component peaking at 300 msec (P300), and large "slow-wave" (SW) components (3). The distinction between the types of ERP waveforms made it possible for us to develop a discriminant function in which ERP's to individual tones were classified as "rare" or "frequent" (4). When a "correct" classification was defined as the categorization of an ERP elicited by a rare tone as "rare" and by a frequent tone as "frequent," the discriminant function formed from the ERP data of one group of subjects correctly classified 81 percent of all ERP's from a group of new subjects. Although the classification technique was successful, the reasons for misclassifying 19 percent of the trials remained unclear. An analysis of the waveforms associated with the misclassifications suggested that the erroneous classifications reflected systematic trial-to-trial variations in the ERP waveforms. Some of the "rare" events seemed to elicit a "frequent" waveform, and vice versa (5). Since the underlying assumption of research involving ERP's is that the ERP's elicited by all occurrences of a particular type of event are identical, such trial-to-trial variations in the ERP required further examination.

Inspection of the trial-to-trial waveform measures suggested that the variations might have been due to short term sequential dependencies. Remington (6) and others (7-10) have demonstrated sequential dependencies in choice tasks, in which reaction time (RT) on any given trial is sensitive to the specific sequence of preceding events. These sequential effects have been attributed by some to trial-to-trial changes in the subject's expectancies (9, 10). Since expectancy has been implicated as one determinant of the ERP waveform, we attempted to determine whether the waveform of the ERP exhibits similar sequential dependencies.

Seven subjects listened to series of regularly presented tone bursts. On each trial a high-pitched and a low-pitched tone were equally likely to occur (11). The subject was instructed to count the high-pitched tones silently and to report the count after each block of 200 trials. In a second condition, the probabilities of the high- and low-pitched tones were changed to .3 and .7, respectively (12). Each subject was tested on 800 to 1600 trials, depending on the condition.

During testing, the subject was comfortably seated in a reclining chair in a well-lighted experimental room. The electroencephalogram (EEG) was recorded with Burden Ag-AgCl electrodes from F₇, C₇, and P₇ (according to the 10-20 system) which were referred to a linked mastoid electrode, with a wrist ground. The band pass of the amplifier system was set for a time constant of 0.8 second and an upper half-amplitude frequency of 35 hertz. Additional electrodes (Beckman) were situated above and on the outer margin of the right eye to record eye movement and blink potentials. On each trial, a 768-msec epoch of the EEG, beginning 100 msec before the stimulus onset, was digitized from each of the recording channels (at a rate of one sample every 3 msec) and stored on digital magnetic tape. The EEG epochs contaminated with eye movement or blink artifacts were excluded from the subsequent waveform analysis. All trials entered into the tabulations of sequences.

Remington's terminology (6) will be followed. An *A* represents whichever stimulus event occurred on trial *N* (a first-order sequence). For the second-order sequences there were 2 possible patterns of stimuli on trials *N*-1 and *N*, *AA* or *BA*. Similarly there were 4 possible third-order patterns (*AAA*, *BAA*, *ABA*, or *BBA*), 8 fourth-order patterns, and 16 fifth-order patterns. When sequences terminated with a high-pitched tone, an *A* in a sequence represents the occurrence of a high-pitched tone and a *B* that of a low-pitched tone. When the sequences terminate with a low-pitched tone, the labels are reversed. A waveform measure can be plotted for each of the possible sequences and a tree diagram constructed by connecting the points in each order to the related points in the higher and lower orders. For instance, the third order sequences *ABA* and *BBA* are related to the second order sequence *BA* by the occurrence of either an *A* or a *B* on trial *N* - 2.

Branches at each node, which systematically diverge to high orders, indicate differential effects of the preceding stimuli in the sequence on the dependent variable on trial *N* (Fig. 1).

The averaged ERP waveforms (from C₇) for the sequences of the outer limbs of the tree structure are shown for one subject in Fig. 2. Large discriminant scores reflect large P300 components (and the associated N200 and SW components). There is systematic variation in the waveform of the ERP as a function of the sequence of preceding stimuli. The size of the P300 complex elicited by an *A* increases with the number of *B* stimuli that precede it (the ascending limb of the tree), and the size of the P300 complex decreases as runs of *A* stimuli of increasing length precede a given *A*. The influence of preceding stimuli on the ERP elicited on trial *N* extends at least to trial *N* - 4 (Fig. 1a) (13). The discriminant score variations seem to result mainly from amplitude changes of the waveform components and not ~~X~~ large shifts in latencies of the components (Fig. 2) (14).

A



in the unequal probability condition (.3/.7), the tree structures for the high- and low-pitched tones are displaced (Fig. 1, b and c). The discriminant scores for each sequence are generally larger for the stimuli with a low probability and smaller for those with a high probability (.15). The average displacement, however, is no larger than the range of the discriminant scores observed for fifth-order sequences in each of the panels (Fig. 1). The sequential determinants of waveform variability seem to be at least as potent as the determinants of the ERP waveform associated with changing levels of stimulus probability.

The tree structure reported here is similar to the RT trees of Remington (6) and Falmagne *et al.* (7). The analogous effects in the two cases are the enhancement of the P300 complex and the prolongation of RT with longer sequences of preceding n's. If, as has been argued (9), RT increases as an inverse function of expectancy, a similar relationship between expectancy and ERP waveforms can be assumed. We proceeded, therefore, to develop a model, based on the concept of expectancy to describe the sequential dependencies in ERP waveform.

In serial RT tasks, when the intertrial interval is less than 2.0 seconds, the effect of a stimulus sequence on the expectancy of a stimulus event is presumed to function as follows. The subject forms a local (as opposed to a global) subjective probability distribution that reflects event frequency within a "sliding window." The more frequently an event occurs within that window, the greater is the subjective probability (expectancy) that the event will recur. When the next event in the sequence confirms the expectations induced by the probability distribution, RT ~~time~~ is shorter than if the less expected event occurs.

In our experiment, the amplitude of the P300 complex (as measured by the discriminant score) seems to be larger when the expectation is disconfirmed than when it is confirmed by the eliciting

event. Thus, a model accounting for the waveform data should estimate the expectancy the subject has for an event as a function of the preceding sequence of stimuli. We assume expectancy to be determined in a linear additive fashion by three factors: (i) the memory for event frequency within the prior stimulus sequence, (ii) the specific structure of the prior sequence, and (iii) the global probability of the event.

The assumption that the locally operating, subjective probability distribution depends on a sliding window implies that the magnitude of effect of a stimulus on the expectancy for succeeding stimuli is a decaying function of sequential position (or time) (10). We assume that the effect of a stimulus on responses to succeeding stimuli is governed by an exponential decay process (9). The specific form of the "memory" (M) expectancy function for event λ on trial N as a function of the sequence of past events S_i is assumed to be

$$M_{\lambda N} = \sum_{i=N-1}^{N-m} \alpha^i S_i \quad (1)$$

where

$$S_i = \begin{cases} 0 & \text{for } (S_i = n) \\ 1 & \text{for } (S_i = \lambda) \end{cases}$$

and where m equals the order of the sequence (here, $m = 5$). The constant α corresponds to the rate of decay in memory of prior stimulus information ($0 < \alpha \leq 1$); small values of α indicate that only very recent events contribute to expectancy (16).

Alternations in the stimulus sequence generate expectancies that the alternation pattern will continue (10, 17). With regard to alternations, our model assumes that (i) a positive expectancy is generated for the stimulus on trial N that fits the alternation pattern, and a negative expectancy is generated for one that breaks the pattern; (ii) the magnitude of the alternation factor should grow (linearly) with the number of consecutive prior alternations; and (iii) a minimum of two prior alternations are necessary to induce an alternation set. Thus, each stimulus sequence was assigned an alternation factor $A(S_i)$, whose value (-3 to +3) was generated by these assumptions (18).

The probability (P) that a stimulus will occur affects the discriminant score independently of sequential effects (Fig. 1). It may be conceived of as a reflection of long-term memory, or as a nonzero asymptote of the decaying short-term memory process that governs the more recent sequential effects. Similar effects of global probability operate on reaction times (6, 7). We assumed that the three determinants of expectancy ($M(S_i, \alpha)$, $A(S_i)$, and P) combine linearly and in an additive fashion to contribute to overall event expectancy and, therefore, to predict the magnitude of the discriminant score.

We first determined the memory decay constant α in Eq. 1 that would provide the best linear relationship between discriminant scores and the memory expectancy factor for the probability conditions, $P = .3, .5$, or $.7$. The value of α that maximized the linear correlation between M and the discriminant scores did not differ among the three conditions (19). The mean value of α , 0.6, was thus selected as the memory decay rate for all conditions.

We performed a multiple linear regression analysis in order to determine the equation relating the values of the fifth-order discriminant scores to M , P , and A :

$$\text{Expectancy} = 0.235M + 0.033A + 0.505P - 0.027 \quad (2)$$

In Fig. 3, the observed expectancies (measured as discriminant scores) for all three probability conditions are plotted as functions of the expectancy values derived from Eq. 2 (20). The regression equation accounted for approximately 78 percent of the variance ($R^2 = .881$) (21).

The multiple regression analysis was repeated with pairs of factors to evaluate the incremental proportion of variance accounted for by each factor. The largest gains were added by including the P (38 percent) and M (49 percent) factors; a small predictive increase was gained by including A (5 percent) (22). Alternations occurred in only a small number of sequences (4 of 16) and their effect on the ERP waveform counters attempts to explain these results in terms of habituation. If the mere occurrence of a stimulus affects all subsequent stimuli through habituation, the precise pattern of stimuli within a sequence should not materially affect the results.

Our model extends hypotheses previously advanced to account for the effects of event probabilities on the waveform of ERP's (23). The amplitude of the P300 complex increases as the expectancy of a stimulus decreases, and multiple factors combine to determine the expectancy that the subject associates with individual stimuli. Moreover, the effect of expectancy can be inferred to be related to dynamic processes that develop over short progressions of stimuli spanning time intervals of only a few seconds. Thus, caution should be exercised in the interpretation of changes in the waveform of the average ERP. The

validity of the common assumption that the average is computed over a homogeneous data set must be carefully evaluated for each experiment. For example, whenever the global probability of an event is increased, there is a corresponding increase in the number of runs of that stimulus in the series. If trials in such a series are averaged without regard to their serial position, the increased proportion of trials following long runs of like stimuli may well reduce the amplitude of the P300 complex. Also, an examination of the behavior of the discriminant scores obtained in our previous work on the classification of single-trial ERP's (4) suggests that many of the errors of classification may have been due to sequential effects.

It is hardly surprising to find that the organism's response to "identical" stimuli is in flux. The nervous system is not a passive recipient of inputs; rather it is a dynamic system that continuously generates hypotheses about the environment. The P300 seems to be associated with the evaluation of such contextual hypotheses.

KENNETH C. SQUIRES*
CHRISTOPHER WICKENS
NANCY K. SQUIRES
EMANUEL DONCHIN

Department of Psychology,
University of Illinois,
Champaign 61820

References and Notes

1. J. M. Ford, W. T. Roth, S. J. Dinks, H. S. Kopell, *Science* **181**, 465 (1973); S. A. Hillyard, R. F. Hink, V. L. Schwent, T. W. Picton *ibid.* **182**, 177 (1973); W. Ritter and H. G. Vaughan, Jr. *ibid.* **164**, 326 (1969); L. Kohn and M. J. Martz, Jr., in *Attention and Performance*, S. Kornblum, Ed. (Academic Press, New York, 1973), vol. 4, p. 175; T. W. Picton and S. A. Hillyard, *Electroencephalogr. Clin. Neurophysiol.* **36**, 191 (1973); W. Ritter, R. Simson, H. G. Vaughan, Jr., *ibid.* **33**, 247 (1972); D. B. D. Smith, E. Donchin, L. Cohen, A. Starr, *ibid.* **28**, 146 (1971); R. T. Wilkinson and M. V. Lee, *ibid.* **30**, 411.
2. P. Tieting, S. Sutton, J. Zubin, *Psychophysiology* **7**, 385 (1970).
3. N. K. Squires, K. C. Squires, S. A. Hillyard, *J. Exp. Psychol.: Hum. Percept. Perform.* **1**, 268 (1975); K. C. Squires, E. Donchin, R. Heining, G. McCarthy, *Electroencephalogr. Clin. Neurophysiol.*, in press.
4. K. C. Squires and E. Donchin, *Electroencephalogr. Clin. Neurophysiol.*, in press.
5. It is unlikely that the variations were due to sensory factors since the two auditory stimuli were suprahymnal and clearly distinguishable. It is also unlikely that they were due to gross changes in attention level since, over the short blocks of trials, procedural and task parameters remain identical.
6. R. J. Fennington, *J. Exp. Psychol.* **82**, 250 (1969).
7. J. C. Falmagne, S. P. Cohen, A. Bjwede, in *Attention and Performance*, P. M. A. Rabbitt and S. Donchin, Eds. (Academic Press, New York, 1975), vol. 5, p. 296.



8. S. Kornblum, in *Attention and Performance*, S. Kornblum, Ed. (Academic Press, New York, 1973), vol. 4, p. 259.
9. R. J. Audley, *ibid.*, p. 509.
10. D. R. J. Laming, *Mathematical Psychology* (Academic Press, New York, 1973), p. 197.
11. A tone burst was presented every 1.3 seconds through TDH-35 earphones. Each stimulus had a total duration of 60 msec, including 10-msec rise and fall times, and was gated in random phase. The frequency of the high-pitched tone was 1500 hertz and that of the low-pitched tone was 1000 hertz. Both stimuli were 60 db sound pressure level (SPL) against a continuous background of wide-band noise at 55 db SPL. The sequence of stimuli was completely random except for the constraint that each stimulus occurred with a probability of .5.
12. Subjects were tested in the unequal probability condition either in a second experimental session or after a break in testing during which the subject left the experimental chamber. The separation between conditions was designed to eliminate confusion about the probabilities of occurrence of each tonal stimulus. The subjects were thoroughly briefed about the stimulus probabilities and the mode of random selection of stimuli.
13. The tree structure continued to diverge at least back to trial N-6. As the number of preceding stimuli increased to five and six, the mean discriminant scores increased to 3.7 and 4.07 units, respectively. For increasingly long runs of preceding stimuli the corresponding scores were 1.21 and 1.15.
14. Since the observed changes in waveform statistics as a function of order duplicate the variations in choice RT in analogous tasks, latency shifts in the evoked components which were comparable to the RT latency variations might have been expected. Latency shifts of components such as P300 would yield variations in the discriminant score since it is calculated for fixed latencies. Remington (6) reported changes in the RT of about 20 msec between first order (x) sequences (290 msec) to fifth-order sequences (310 msec) and about 37 msec between the extreme fifth-order sequences (mean RT for sequence AAAAA was 273 msec). Similar variations in the latency for P300 were not seen in the averaged ERP waveforms, but such small latency shifts are probably beyond the resolution possible with these data. Furthermore, it has been argued (8) that sequentially related latency differences in RT are primarily a consequence of repetitions and alternations of the response rather than of the stimulus. Thus, if the speed of processing a stimulus remains relatively unaffected by sequential effects (particularly with simple stimuli) in the RT paradigm, we can assume that such would also be the case in the current paradigm, and therefore the differences in the discriminant scores primarily reflect differences in amplitude rather than in latency.
15. Repeated measures analysis of variance showed significant main effects of both sequence [$F(10,180) = 6.61, P < .001$] and stimulus for probability [$F(1,6) = 8.91, P < .025$]. The interaction of sequence and stimulus was not significant.
16. In Fig. 1, only x's contribute to the value of M . Thus, in the case of the prior sequence containing only x's (xxxxx), the values of all S_i and the resultant memory factor will be equal to 0.
17. When the discriminant score was plotted as a function of the memory factor alone, certain sequences had discriminant scores which did not fall at their orderly, predicted position. For example, the last x in the sequence AAAAA had a much smaller discriminant score than predicted. However, with this particular sequence expectancies for another A would be elevated because the event x on trial n is consistent with the pattern of alternations set up by the sequence.
18. Of the 16 fifth-order sequences, 4 met requirement (iii) and thus had nonzero alternation factors; they were ABAAB (1.21), ABAAB (1.3), ABAAB (1.3), and ABAAB (1.2).
19. The three obtained values of α were 0.58, 0.60, and 0.61 for $P = .3, .5$ and $.7$, respectively.
20. To evaluate the extent to which the expectancy function fit the data for individual subjects, linear correlation coefficients were calculated for each subject in each condition. The mean correlation coefficient values were $-.313, -.578$, and $-.536$ for $P = .3, .5$, and $.7$, respectively.
21. Regression analyses were also performed on the individual-subject data, yielding statistically significant multiple R values in all cases, ranging from .426 to .840 with a mean of .628.
22. In Eq. 2, only the first-order terms have been used. A better fit might have been obtained had interactions between factors or higher order terms been included (Fig. 3). For example, if separate regression lines were fit for the three probability values, the slope of the line for the $P = .7$ condition would be greater than that of the other two. Furthermore, the degree of predictive linear fit seems to differ between conditions, being maximum for the $P = .5$ condition (for this condition a multiple regression of the discriminant score upon the M and A factors produced a multiple R value of .916).
23. K. C. Squires, S. A. Hillyard, P. H. Lindsay, *Percept. Psychophys.* 13, 25 (1973); Tueting *et al.* (2) also noted effects of both repeated and alternated events and related their results to the "unexpectedness" of the outcome.
24. The discriminant score is a combined measure of the N200, P300, and SW components of the ERP at the three electrode sites that was developed according to a stepwise discriminant analysis procedure (26), which optimally discriminates between ERP's elicited by rare and frequent stimuli (3, 4). The use of such a statistic has certain advantages; since it is a combined measure of several ERP amplitudes, it is less susceptible to EEG noise than individual base-to-peak amplitudes; it includes more waveform information, and it is a measure that can be applied to any subject's data without adjustment. The latencies at which ERP amplitudes were taken for inclusion in the discriminant score were 104, 188, 248, 320, 356, and 380 msec for F_1 ; 128, 236, 332, 356, 380, and 668 msec for C_1 ; and 224, 344, 380, 476, 536, and 572 msec for P_1 .
25. E. Donchin, *IEEE Trans. Biomed. Eng.*, 13, 131 (1966); NASA Spec. Publ. SP-191 (1969), p. 199; R. Herning, *Electroencephalogr. Clin. Neurophysiol.* 38, 51 (1975); E. Donchin, E. Callaway, R. Jones, *ibid.* 29, 429 (1970).
26. Combining data across stimuli was justified because the tree structures for each were essentially identical. A repeated measures analysis of variance yielded a significant sequence effect [$F(10,180) = 106.5, P < .001$], but the effect of differing signals was nonsignificant, as was the signal by sequence interaction. High-pitched tones (counted by the subject), however, tended to yield larger discriminant scores than the low-pitched tones. This counting effect was significant ($P < .01$) when we tested it using difference scores for matched pairs of fifth-order sequences, but it was small relative to the sequence effect.
27. Supported by the Advanced Research Projects Agency of the Department of Defense under contracts DAHC 15-73 C 0318 and ONR US NAVY N-0002 to E. D. The technical assistance of T. Dunn and S. Petuchowski and the helpful comments of G. McCarthy and R. Horst are gratefully acknowledged.

* Present address: Department of Medicine, University of California, Irvine 92616.
† Reprint requests should be addressed to E. Donchin.

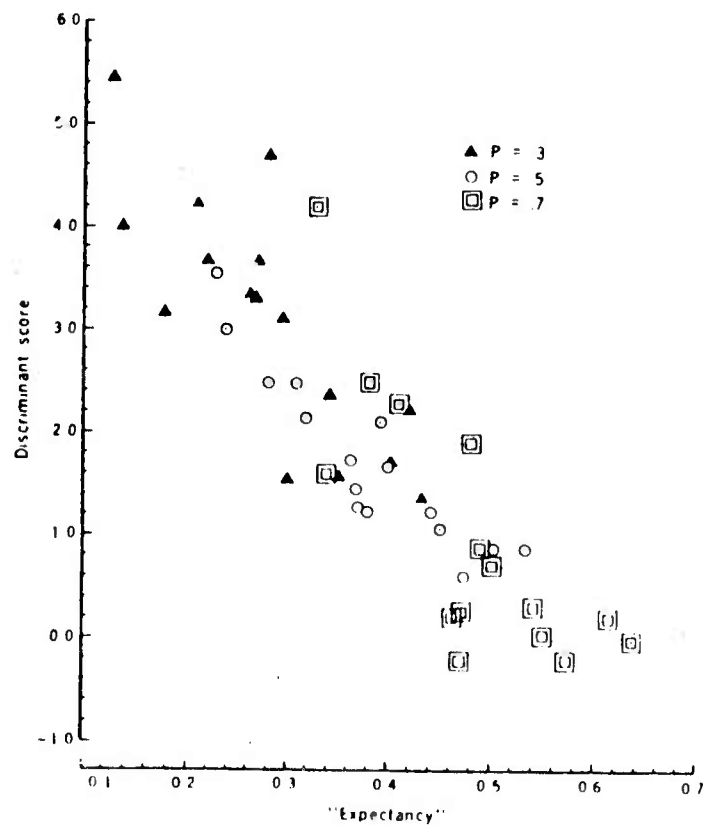
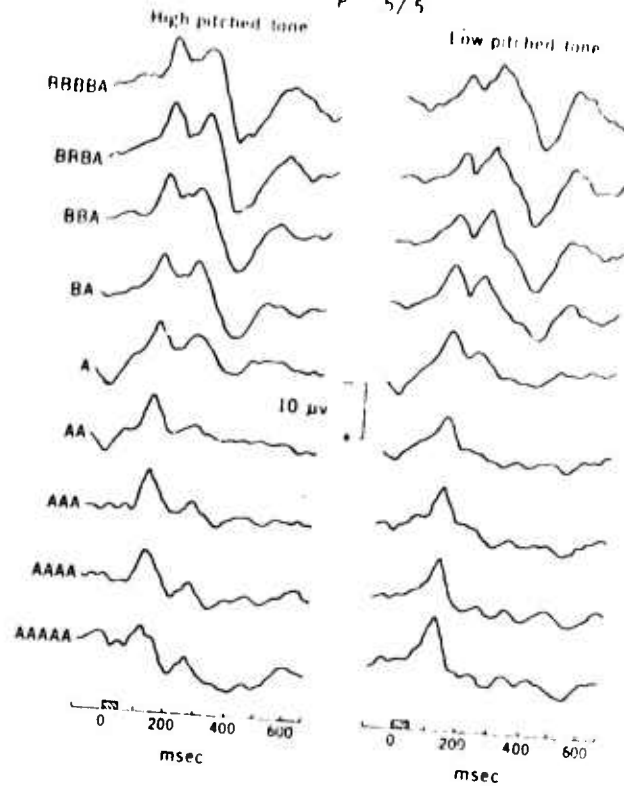
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Fig. 1. Tree diagrams of discriminant scores [a composite measure of the ERP waveform elicited on trial N (24, 25)] as a function of the sequence of preceding stimuli. The discriminant score is given in arbitrary units. Within each order (1 to 5), the stimulus sequence is labeled, and related sequences are connected across orders. (a) Mean of all occurrences of each sequence with stimulus probabilities of .5/.5 (26). (b) Probability of stimulus presentation equal to .3 (x represents the high-pitched tone). (c) Probability of stimulus presentation equal to .7 (x represents the low-pitched tone).

Fig. 2. Averaged ERP waveforms from the vertex (C_1) lead for sequences that form the outer limbs of a tree diagram with the probabilities of occurrence of each signal equal to .5. Vertex negativity is plotted upward. Fig. 3. Observed discriminant score plotted as a function of the predicted expectancy score for stimulus presentation at three probabilities of stimulus occurrence.

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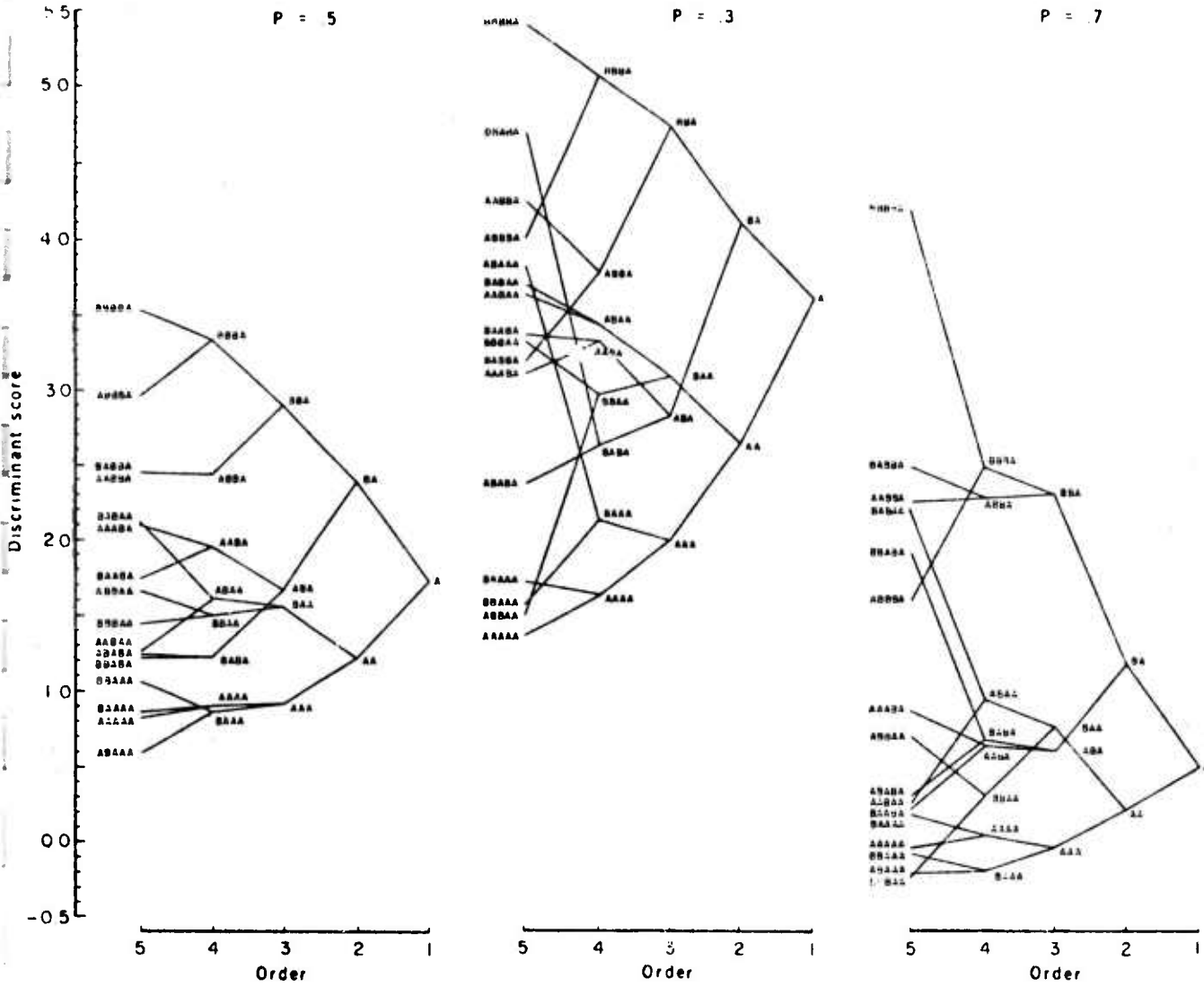


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P = 5

P = .3

P = 7



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FIG. 1

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BISENSORY STIMULATION: INFERRING DECISION-RELATED
PROCESSES FROM THE $\overline{P300}$ COMPONENT¹

Nancy K. Squires, Emanuel Donchin, and Kenneth C. Squires

Cognitive Psychophysiology Laboratory

Department of Psychology

University of Illinois

Champaign, Illinois 61820

and

Stephen Grossberg

Department of Mathematics

Boston University

Boston, Massachusetts 02215

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Running Title: Bisensory Stimuli and the P300 Component

Send proofs to: Dr. Emanuel Donchin
Department of Psychology
University of Illinois
Champaign, Illinois 61820

ABSTRACT

Three experiments were conducted to evaluate the $\overline{P300}$ component of the human evoked response as an index of bisensory information processing. On different blocks of trials subjects were presented with auditory stimuli alone, visual stimuli alone or with audio-visual compounds. In each series there were two possible stimuli, one of which was presented less frequently than the other; the subjects' task was to count the infrequent stimuli. In the first two experiments the information in the two modalities was redundant while in the third the modalities provided non-redundant information. With redundant information, the $\overline{P300}$ latency indicated bisensory facilitation when the unimodal $\overline{P300}$ latencies were similar; when the unimodal latencies were dissimilar, the bisensory $\overline{P300}$ occurred at the latency of the earlier unimodal $\overline{P300}$. Reaction times paralleled $\overline{P300}$ latency. When the information in the two modalities was non-redundant both $\overline{P300}$ amplitude and reaction time data indicated interference between the two modalities, regardless of which modality was task relevant. $\overline{P300}$ latency and reaction time did not covary in this situation. These data suggest that $\overline{P300}$ latency and amplitude do reflect bisensory interactions, and that the $\overline{P300}$ promises to be a valuable tool for assessing brain processes during complex decision making.

INTRODUCTION

The $\overline{P300}$ component of the event-related brain potential (ERP) which can be recorded from the human scalp seems to be a sensitive measure of information processing (see Price and Smith, 1975, for a bibliography). Since the $\overline{P300}$ is a multifaceted measure whose amplitude, latency and distribution over the scalp may be independently determined by different aspects of the cognitive process, it might well prove to be a richer measure than such traditional indices of processing as reaction time (RT) [for example, $\overline{P300}$ latency may index the time of occurrence of a cognitive process (Kutas and Donchin, in press), its scalp distribution may index the nature of the task (Courchesne, Hillyard, and Galambos, 1975), while $\overline{P300}$ amplitude may index expectancy for the eliciting event (Donchin, Kubovy, Kutas, Johnson, and Herning, 1973; Squires, K., Wickens, Squires, N., and Donchin, in press)], especially since the ERP can be used to assay ongoing cognitive processes without requiring an overt response by the subject. For example, Squires, K., Wickens, Squires, N., and Donchin (in press) demonstrated that $\overline{P300}$ amplitude reflects rapid changes in a subject's "expectancies" which parallel the effects of sequential dependencies between reaction times (Falmagne, Cohen, and Dwivedi, 1975; Remington, 1969). The $\overline{P300}$, however, revealed these expectancy fluctuations during a task which required no overt responses.

Despite the potential utility of $\overline{P300}$ and other ERP measures, few attempts have been made to utilize the growing body of knowledge about cognition in identifying the functional determinants of the various ERP components or to utilize $\overline{P300}$ in clarifying issues of human information processing. The procedures and terminology of the two research areas have remained largely distinct. There is a clear need for experiments which use paradigms from the information processing literature to evaluate the utility of the ERP as a measure of complex processes. Such experiments are also likely to help clarify the functional significance of $\overline{P300}$.

Two issues are specifically addressed in the experiments reported here. The first concerns the ERP manifestations of the way in which subjects deal with multiple

sources of information. Our work most clearly follows that of Garner and his co-workers (see Garner, 1974, for a review) who have shown, using multi-dimensional stimuli, that the nature of the dimensions or information channels, as well as their redundancy, determines the manner in which the subjects process the information. The second and third experiments are particularly relevant to this issue.

The second related area of interest is the relationship of P_{300} and reaction time measure. Previous research suggests that P_{300} latency and RT sometimes covary, longer RTs being associated with longer P_{300} latencies (e.g., Picton, Hillyard, and Galambos, 1974; Ritter, Simson, and Vaughan, 1972; Rohrbaugh, Donchin, and Eriksen, 1974). Other investigators report stable P_{300} latencies despite varying RTs (e.g., Karlin and Martz, 1973; Squires, K., Wickens, Squires, N., and Donchin, in press). Since reaction time appears to be multiply determined (Felfoldy, 1974) it may be the case that only some of the variables affecting reaction time also influence the P_{300} (e.g., Wilkinson and Spence, 1973). Experiment III was concerned with this problem.

As these studies required the simultaneous presentation of auditory and visual stimuli, the initial step was to determine the feasibility of analyzing the contribution of each element to the bisensory ERP. Previous studies have generally employed simple, non-simultaneous sensory events, assuming that the simultaneous occurrences of more than one event would make interpretation of the ERP difficult, leading to serious restrictions on the procedures that can be examined via ERP techniques. The first experiment, then, investigated the dissociability of the effects of two simultaneously presented stimuli. To facilitate interpretation, only redundant information was used in this initial experiment.

EXPERIMENT I - METHODS

Subjects. Six normal adults (ages 18-32, 3 female and 3 male) including experimenters NS and KS, served as subjects. The volunteer subjects were paid for their participation. (NS and KS appear as subjects "1" and "2" in all figures and tables.)

Stimuli. The auditory stimuli were 80 dB SPL tone bursts delivered binaurally

through TDH-39 earphones against a continuous background of white noise at 55 dB SPL at a rate of one every 1.3 sec. Two tone frequencies were used, 1000 Hz and 1500 Hz. Each tone burst was 60 msec in duration including 10 msec rise-fall times. The visual stimuli were presented via two fields of an Iconix model 6137 four-field tachistoscope and were 50 msec in duration. A left-pointing and right-pointing arrow were outlined in black (visual angle of 1°) on a blank white field (visual angle of 6°). The luminance of these fields was 20 ft-L, measured with a Spectra brightness spot meter.

Recording System. The EEG was recorded from 5 electrode sites (Oz, Pz, Cz, Fz, and FPz according to the 10-20 system) referred to linked mastoids. The ground electrode was on the back of the right hand. Burden Neurological Institute Ag-AgCl electrodes affixed with collodion were used for scalp recording. Beckman Biopotential electrodes were used for the reference and ground electrodes. In addition, right supra-orbital and canthal electrodes were used to record the electrooculogram. Subjects were instructed not to move their eyes excessively, and the averaged EOG indicated that eye movement artifacts were indeed negligible.

The EEG was amplified with Grass 7P122 amplifiers (time constant 0.8 sec and upper half-amplitude frequency 35 Hz) and was sampled for 768 msec beginning 100 msec prior to stimulus onset at a rate of one sample every 3 msec.

Data Collection. Stimulus presentation and data collection were under the control of a PDP 11/40 computer (see Donchin and Heffley, 1975). The data acquisition was monitored on-line and the averaged ERPs for each stimulus type for each block of trials were stored on digital magnetic tape for later analysis.

Procedure. Bernoulli trials were presented in blocks of 50. In each block, one of the two possible outcomes had a 0.10 probability of occurrence (the "rare" stimulus) and the other had a 0.90 probability of occurrence (the "frequent" stimulus). The subject, seated in a reclining chair, was asked to count the number of rare stimuli in each block, to be reported at the end of the block. In all the experiments counting performance was virtually perfect.

There were seven different experimental conditions in which the stimuli were either

unimodal or bimodal: 1) auditory stimuli with a frequent 1000 Hz tone and a rare 1500 Hz tone; 2) auditory stimuli with the probabilities of the two stimuli reversed; 3) visual stimuli with a frequent left-pointing arrow and a rare right-pointing arrow; 4) visual stimuli with the probabilities of the two stimuli reversed (conditions 2 and 4 served only to confirm that the $\overline{P300}$ was related to stimulus probability and will not be discussed further); 5) bimodal stimuli with the frequent stimulus being the simultaneous presentation of the 1000 Hz tone and the left arrow, and the rare stimulus being the compound of the 1500 Hz tone and the left arrow ("variable auditory - constant visual"); 6) bimodal stimuli with the frequent stimulus being the 1000 Hz tone and left arrow and the rare stimulus being the 1000 Hz tone and right arrow ("constant auditory - variable visual"); and 7) bimodal stimuli with the frequent stimulus the 1000 Hz tone and the left arrow, and the rare stimulus the 1500 Hz tone and right arrow ("variable auditory - variable visual"). Thus in this last condition the information supplied by the two modalities was redundant.

The subject was informed prior to each block of trials which stimuli would be presented. Each type of series was presented twice to each subject in the course of a two-hour session so that each rare-stimulus ERP was the average of approximately 30 trials. The order of presentation was counter-balanced across subjects.

RESULTS

P300s to unimodal stimuli. As in previous studies (e.g., Ritter and Vaughan, 1969; Ruchkin and Sutton, 1973; Squires, N., Squires, K., and Hillyard, 1975; Tueting, Sutton, and Zubin, 1971) the rare stimuli elicited large $\overline{P300}$ components. This is shown in Figure 1 where the ERPs associated with the rare and frequent auditory stimuli are superimposed on the left column, and the ERPs to the rare and frequent visual stimuli are superimposed in the right column. For each subject the latency of the "visual

 INSERT FIGURE 1 ABOUT HERE

"P300" was much longer than that of the "auditory P300" ($t = 10.91, p < 0.001$). The mean peak latency of the auditory P300 was 360 msec and the mean peak latency of the visual P300 was 500 msec. The two components, however, exhibited similar scalp-amplitude distributions. Table 1 (a and b) gives the mean P300 amplitudes at each electrode site for the auditory and visual ERPs. The peak of the P300 component was

 INSERT TABLE 1 ABOUT HERE

chosen as the largest positive deflection within a latency range chosen by visual inspection of each ERP waveform and its amplitude was measured relative to the 100 msec pre-stimulus baseline. The auditory P300 was of somewhat smaller amplitude than the visual P300 but for both modalities the largest P300 amplitudes were recorded at the parietal electrode, decreasing rapidly posteriorly and more slowly frontally. The variation in amplitude across electrode sites was statistically significant ($F(4,20) = 12.19, p < 0.01$), while the effect of modality was not significant ($F(1,5) = 3.28$) due to the U-shaped nature of the scalp distribution; the interaction of electrode site and modality was significant ($F(4,20) = 6.25, p < 0.01$).

P300s to bimodal stimuli. When an unchanging stimulus in a second modality was presented simultaneously with the Bernoulli sequence in the first modality (conditions 5 and 6) the rare stimulus evoked a P300 component that closely resembled the P300 elicited by that stimulus presented alone. The left column of Figure 2 presents the superimposed tracings of ERPs elicited by the rare auditory stimulus when presented alone (solid line) and when accompanied by the frequent (unchanging) visual stimulus (dashed line). The analogous data for the visual ERPs are shown on the right. There

 INSERT FIGURE 2 ABOUT HERE

were no statistically significant differences in amplitude or latency of P300 due to the addition of an unchanging, irrelevant, stimulus in the other modality. The scalp

distributions of $\overline{P300}$ amplitude also remained unchanged (Table 1, c, d), maintaining a parietal maximum.

When rare stimuli occurred simultaneously in the two modalities (condition 7), the $\overline{P300}$ mirrored the $\overline{P300}$ elicited by the auditory element alone (condition 5). This is demonstrated in Figure 3 where the ERPs to the "rare auditory - frequent visual" combinations are compared with those to the "rare auditory - rare visual" combinations. There were no statistically significant differences in amplitude or latency of the $\overline{P300}$ s thus compared. The similarity of these waveforms suggests that the rare visual stimulus was not contributing to the $\overline{P300}$ in condition 7.

INSERT FIGURE 3 ABOUT HERE

DISCUSSION

Apparently the contributions of the two modalities to the bisensory $\overline{P300}$ can be readily determined. The auditory and visual $\overline{P300}$ s differed in latency by 140 msec, and when the two series were redundantly combined, the resulting $\overline{P300}$ occurred at the latency of the auditory $\overline{P300}$ and showed no effect (on latency or waveshape) of the visual stimulus. Choice reaction times in analogous situations behave in much the same way; when the choice reaction times to stimuli in each modality are widely disparate, the reaction time to the redundant bimodal stimulus equals that of the shorter unimodal RT (e.g., Hershenson, 1962; and see Loveless, Brebner, and Hamilton, 1970, for a review of bisensory stimulation).

The predominance of the auditory $\overline{P300}$ might be attributed to a natural auditory predominance deriving from some inherent difference in the processing of auditory and visual stimuli. This interpretation is unlikely, however, in view of the data of Colavita (1974) showing a pronounced visual predominance in a reaction time task with somewhat different auditory and visual stimuli than were used here. Alternatively, the discrimination between the 1000 Hz tone and the 1500 Hz tone might have been easier

than the discrimination between the right-pointing and left-pointing arrows, and the P300 associated with the easier task might predominate. The next experiment addressed this issue.

EXPERIMENT II - INTRODUCTION

A reasonable interpretation of the data of Experiment I is that P300 latency reflects the latency of the decision about the stimulus. It has been previously demonstrated in choice RT experiments (e.g., Biederman and Checkosky, 1970; Felfoldy, 1974; Thurmond and Alluisi, 1963) that decision latency varies with stimulus discriminability. Furthermore, the degree of facilitation of the bisensory RT depends upon the similarity of the RTs to the two component stimuli. In situations like the one in Experiment I where the individual RTs are quite different, no bisensory interaction is found, but with similar component RTs, the RT to the compound is shorter than either of the unimodal RTs (e.g., Biederman and Checkosky, 1970; Wood, 1974). Experiment II therefore varied intramodality discriminability to determine whether the auditory predominance of Experiment I was reversible, and whether bisensory facilitation is reflected in P300.

METHODS

Subjects. Six subjects (5 female and 1 male) participated in the ERP section of this experiment, including three subjects from the previous experiment. (Subjects 1, 2, and 6 of that experiment are subjects 1, 2, and 4 here). Seven subjects (including 1 and 2) participated in the RT segment.

Stimuli. Two sets of auditory stimuli were used, 1100 Hz vs 1000 Hz tones (the easy auditory discrimination) and 1100 Hz vs 1060 Hz tones (the difficult auditory discrimination), with the 1100 Hz tone the rare ($P = 0.10$) stimulus in both cases. Similarly, there were two sets of visual stimuli, orange vs blue (the easy visual discrimination) and orange vs yellow (the difficult visual discrimination), with orange the rare stimulus in both cases. The color stimuli were produced by filtering the tachistoscope flashes with opaque-projector filters of various hues.

The stimulus durations and repetition rates in the ERP experiment were the same as in Experiment I. In the RT experiment each stimulus presentation followed the previous response after a random interval of 500-1000 msec.

Procedures. There were eight conditions in this experiment. Four involved unimodal stimuli and four involved bimodal stimuli. The four unimodal stimulus conditions were the easy auditory, difficult auditory, easy visual, and difficult visual discriminations. In the bimodal stimulus conditions each auditory discrimination was paired with each visual discrimination, with the rare events in each modality occurring simultaneously as in the previous experiment.

During ERP recording trials were presented in blocks of 150, with the instruction to count the rare stimuli. Each of the eight conditions was presented three times during the course of two two-hour testing sessions with the order of presentation balanced.

During the reaction-time sessions, one of two buttons was pressed depending upon the stimulus presented. Stimuli appeared in blocks of 100. The RTs reported here are the means of two blocks of trials, one in which the subjects responded with the left hand to rare stimuli and the right hand to frequent stimuli, and one in which the association of hands and stimuli was reversed. While it would have been obviously advantageous to record the RTs at the same time the ERPs were recorded (Donchin and Sutton, 1970) the likelihood that motor potentials (Kornhuber and Deecke, 1965) would contaminate the P300 argued for separate acquisition of these data. Also the reaction-time data were collected primarily to validate any bisensory interactions obtained here by comparing them with previous reports, and not to make direct P300 - RT comparisons.

RESULTS

RT data. Mean reaction times to the rare and frequent stimuli are shown in Table 2. The easy discriminations in the two modalities yielded virtually identical

INSERT TABLE 2 ABOUT HERE

RTs. The RTs for the difficult discriminations were considerably longer. These data replicate previous findings on discriminability and RT (e.g., Thurmond and Alliusi, 1963). The bimodal stimuli whose elements gave widely different RTs (easy auditory - difficult visual and difficult auditory - easy visual) yielded RTs that were significantly less than the longer of the two unimodal RTs ($p < 0.05$ for each comparison) and approximately equalled the earlier of the two unimodal RTs. This was true for both the rare and frequent stimuli in each case. When the RTs to both elements of the compound were more similar (easy auditory - easy visual and difficult auditory - difficult visual), the mean RTs to the bimodal stimuli were shorter than either of the unimodal RTs. This result was statistically significant for the bimodal difficult condition ($F(2,12) = 10.91, p < 0.01$), but not for the bimodal easy condition ($F(2,12) = 3.58, p < 0.10$).

P300 latency. The latency data for the $\overline{P300}$ at the vertex electrode are given in Table 3. (The vertex electrode was used for reasons that will be discussed below.) In general, the relationships among the $\overline{P300}$ latencies in the various conditions

 INSERT TABLE 3 ABOUT HERE

parallel the relationships between the RTs described above, with shorter $\overline{P300}$ latencies corresponding to faster reaction times. The main exception to this is the difficult auditory condition, where the RTs were long compared to the difficult visual condition, while the $\overline{P300}$ latencies in the difficult auditory and difficult visual conditions were almost equal. Since the data were collected with different groups of subjects no clear interpretation can be made of this discrepancy.

P300 amplitude and scalp distribution. The scalp distributions of the $\overline{P300}$ s are shown in Figure 4. All the $\overline{P300}$ distributions are similar, with maximum amplitude at Pz. The bimodal $\overline{P300}$ s tended to be somewhat larger than the unimodal $\overline{P300}$ s.

 INSERT FIGURE 4 ABOUT HERE

Slow-wave amplitude and scalp distribution. The "slow-wave" is another component that has been identified in the ERP to unexpected target stimuli (Squires, K., Donchin, Herning, and McCarthy, in press; Squires, N., et al., 1975). Slow-wave amplitude was measured as the mean base-to-peak amplitude over the last 150 msec of each waveform, and these data are shown in Table 4. In agreement with earlier studies,

 INSERT TABLE 4 ABOUT HERE

the slow-wave is positive at the parietal electrode and negative frontally. In addition, the present experiment provided data on the slow-wave at Oz and FPz where it is positive and negative respectively. The slow-wave distribution and amplitude were unaffected by stimulus modality, task difficulty, and the bimodal vs unimodal nature of the eliciting stimulus. The slow-wave has its lowest absolute amplitude at the vertex; thus to the extent that $\overline{P300}$ and slow-wave overlap temporally, the amount of contamination of base-to-peak measures of $\overline{P300}$ by the slow-wave is minimal at this site. For this reason all between-condition comparisons of $\overline{P300}$ latency and amplitude in the present experiments were made at Cz.

DISCUSSION

Experiment I raised the question of whether the predominance of the auditory element of the bisensory stimulus was due to differences in the discriminability of stimuli within each modality or whether the visual modality always plays a subordinate role in the elicitation of the bisensory $\overline{P300}$. The results of Experiment II indicate that the discriminability of the stimuli within the modality is the factor determining which modality will predominate. While the auditory element predominated in the easy auditory - difficult visual condition, the opposite was true for the difficult auditory - easy visual condition. $\overline{P300}$ appears to be dominated by whichever modality is associated with the earlier decision (as inferred from $\overline{P300}$ latency and RT). When the decisions in the two modalities have approximately the same latencies, the bisensory

$\overline{P300}$ is earlier than either individual $\overline{P300}$. These results are in agreement with the RT literature, where it has been suggested (e.g., Loveless, Brebner, and Hamilton, 1970; Raab, 1962, Wood, 1975) that redundancy gains can be explained by a statistical combination model that assumes that processing of component dimensions proceeds simultaneously (in parallel) and that the RT on each trial is determined by whichever component process is completed first. The amount of redundancy gain will be proportional to the overlap of the unimodal RT distributions. When such gains occur, the variance of the distribution of the bimodal RTs should also be reduced compared to the unimodal RT distributions. Assuming that $\overline{P300}$ latency is correlated with the decision latency, this RT model predicts a decrease in the latency of $\overline{P300}$ and an increase in its amplitude due to the decreased variability in the timing of the decision. Experiment II showed that the decreased latencies of the bimodal $\overline{P300}$ s were indeed associated with increased $\overline{P300}$ amplitudes. (A similar prediction would of course be made by any model that accounted for decreased RT variance with decreased RT.)

One particularly important aspect of these data is the marked effect that stimulus discriminability had on the latency of the $\overline{P300}$. The latency of the $\overline{P300}$ to the 1100 Hz tone, for example, was 60 msec later when paired with a 1060 Hz tone than when paired with a 1000 Hz tone, even though in both conditions the counting performance was nearly perfect. While we have implicated the role of task "difficulty" by our use of the labels "easy" and "difficult," explanations in terms of the salience of the target stimulus (Jenness, 1972), or the magnitude of the template mismatch (Squires, K., Hillyard, and Lindsay, 1973), and so forth may be equally suitable. It was not the purpose of the present experiments to test the adequacy of various existing hypotheses regarding the psychological correlates of the $\overline{P300}$. The point here is that the sensitivity of $\overline{P300}$ latency implies considerable variability across experiments and across subjects due to differences in the stimuli used and the difficulty of the task for the individual subject. The equivalence of late positive waves of varying latencies has sometimes been questioned. For example, Thatcher (in press) has suggested that a $\overline{P300}$ and a $\overline{P400}$ may be different components even though they are recorded under similar

circumstances. Our data suggest, as do others¹ (Kuraz and Donchin, in press; Ritter et al., 1972), that the latency of the late positive component is determined by the latency or the duration of the endogenous process it manifests (Donchin, 1975). A great deal of caution must therefore be used in identifying late components solely on the basis of peak latency. On the other hand, this same result provides encouraging evidence that $\overline{P300}$ latency is indeed a sensitive measure of decision processes in its own right although in the past the major emphasis has been placed instead on $\overline{P300}$ amplitude variations.

While small differences in the scalp-amplitude distributions of the auditory and visual $\overline{P300}$ s were found in the first experiment, no such differences were found in Experiment II when the discriminability of the stimuli within the two modalities were equated. Thus it appears that the auditory and visual $\overline{P300}$ s can be considered to be equivalent components, provided that the conditions under which the auditory and visual $\overline{P300}$ s are elicited have been carefully equated.

EXPERIMENT III - INTRODUCTION

In the first two experiments the two modalities always provided redundant information so that the appropriate response was always perfectly correlated with the stimulus. For a complete assessment of the degree to which $\overline{P300}$ reflects the interactions known to occur between multiple channels of information, it is necessary also to examine the effects of non-redundant information. When subjects are asked to attend to only one of two orthogonally varying dimensions and ignore the other, the task is called a "filtering" task (Posner, 1964). Here stimulus changes occur with and without a change in response. Felfoldy (1974) measured reaction times in a filtering task and demonstrated that both stimulus and response variables influence the total RT. Experiment III looked at whether this is also true of $\overline{P300}$ latency.

An analysis of filtering tasks, however, must take into account the nature of the stimulus dimensions used. Garner (1974) classified pairs of dimensions as "integral" or "separable." For visual stimuli, for example, value and chroma are integral

dimensions, while size and lightness are separable, perceptually independent dimensions. Several converging operations have been used to support this distinction including similarity judgements, perceptual classification tasks, reaction time, and speeded classification (card sorting) tasks (Garner, 1974). With speed measures of performance, redundant integral dimensions facilitate performance but redundant separable dimensions do not (Garner and Felfoldy, 1970; Wood, 1974). With non-redundant dimensions, on the other hand, filtering tasks are completed faster with separable than with integral dimensions (Gottwald and Garner, 1975). While one might expect auditory and visual dimensions to be independent or separable (see Garner, 1974, p. 170), both the $\overline{P300}$ latency and RT data of Experiment II meet the first criterion for integrality: facilitation under conditions of redundant information. However, as Garner has pointed out (p. 132), in circumstances such as those in Experiment II it is to the subject's advantage to attend to both dimensions even when they are by nature separable. A more critical test of the integrality or separability of dimensions comes from procedures where the information provided by the two dimensions is not redundant, and attention to both dimensions would interfere with performance. If the subject cannot exclude the irrelevant dimension the dimensions are integral; if no interference is found the dimensions are separable. Experiment III therefore investigated $\overline{P300}$ and RT measures of information processing with the elements of the bisensory stimuli providing non-redundant information.

METHODS

Subjects. Five subjects (4 female and 1 male) participated in the ERP section of Experiment III, including two (subjects 1 and 2) who had participated in both previous experiments. RTs were taken from the same seven subjects who participated in the RT section of Experiment II.

Stimuli. All stimuli in this experiment were bisensory, audio-visual compounds. The two auditory stimuli were a 1000 Hz tone and an 1100 Hz tone, the "easy auditory" discrimination of the last experiment. The two visual stimuli were an orange

flash and a blue flash, the "easy visual" discrimination. Four types of bisensory stimuli could occur in each block of trials: 1000 Hz - orange ($P = 0.85$), 1000 Hz - blue ($P = 0.05$), 1100 Hz - orange ($P = 0.05$), and 1100 Hz - blue ($P = 0.05$). Thus there were three equi-probable types of rare stimuli, two of which had a rare stimulus in one modality and one with rare stimuli in both modalities. The stimuli were the same on every block of trials; only the task differed.

Procedure. The subject was assigned one of three tasks at the beginning of a block of trials: 1) count all rare (1100 Hz) tones, 2) count all rare (blue) flashes, or 3) count both rare tones and rare flashes, counting a double rare as one. There were 150 stimuli per block, and five blocks were presented in each counting condition in counterbalanced order over the course of two two-hour sessions. In addition, three control conditions were presented in which each of the combinations of auditory and visual stimuli was the frequent, non-counted stimulus, with the exception of 1000 Hz - orange which had been the frequent stimulus in all other blocks. Reaction times were collected in the same manner as in the previous experiment.

RESULTS

Waveforms. The ERPs for two subjects are shown in Figure 5. The data of these subjects were chosen as the most representative of the experimental effects. Each waveform is the difference between the averaged ERP to a particular rare compound and the corresponding ERP to that compound when it was frequent. These subtractions were made in order to show the isolated effects of the various rare events, without any stimulus-specific effects. The solid lines are the waveforms associated with the double-rare stimulus; this same waveform is shown twice, once on the left superimposed

 INSERT FIGURE 5 ABOUT HERE

on the ERP to the auditory rare - visual frequent, and once on the right with the ERP to the auditory frequent - visual rare. The three counting conditions are represented

in the three rows. The amplitude and latency of the double-rare $\overline{P300}$ remained approximately the same across counting conditions, while the amplitudes of the single-rare $\overline{P300}$ s varied with the instructions.

$\overline{P300}$ amplitude and latency. The latencies of the $\overline{P300}$ s to the double-rare stimuli and to the auditory rare (visual frequent) stimulus were about the same, 350-355 msec in every counting condition (Table 5). The latency of the visual rare (auditory frequent) $\overline{P300}$ was 40-50 msec longer. These latencies were all unaffected by the counting task.

 INSERT TABLE 5 ABOUT HERE

The amplitude of the $\overline{P300}$ to the double-rare stimulus was consistently greater than that of either single-rare $\overline{P300}$ and was unaffected by the counting condition. For the single-rare $\overline{P300}$ s the maximum amplitude occurred when only rares in that modality were being counted, minimal when stimuli in the other modality were counted, and intermediate when both were counted.

Reaction times. The mean reaction times to all four stimuli in each of the three conditions are shown in Table 6. RTs to rare stimuli in the task-relevant modality combined with a frequent in the irrelevant modality were much longer than those to the

 INSERT TABLE 6 ABOUT HERE

double-frequent stimuli, for both auditory and visual modalities (a difference of 128 msec for the auditory in the "attend-auditory" condition, $p < 0.001$, and 123 msec for the visual in the "attend-visual" condition, $p < 0.001$). A rare stimulus in the irrelevant modality also lengthened the reaction time, but by a smaller amount (42 msec for irrelevant visual in the attend-auditory condition, $p < 0.05$, and 66 msec for the irrelevant auditory in the attend-visual condition, $p < 0.01$). The RT to the double-rare stimulus was significantly shorter than to the single auditory rare in the auditory condition (25 msec, $p < 0.01$), but not significantly shorter in the attend visual

condition (15 msec). When subjects were instructed to attend to both modalities the RTs to all stimuli were lengthened over the single-modality conditions. (E.g., the mean RT for double-frequent stimuli in the attend-both condition was 19 msec longer than in the attend-auditory condition and 41 msec longer than in attend-visual.)

P300 scalp distribution. The scalp-amplitude distributions of $\overline{P300}$ are given in Figure 6 for each of the three types of rare stimuli. The $\overline{P300}$ to the auditory frequent - visual rare (bottom frame) had a parietal maximum and resembled the distribution in the "easy-visual" task of Experiment II. However, the distributions for the auditory rare - visual frequent (middle frame) and the double-rare $\overline{P300}$ (top frame) were more equipotential than those shown before (Figure 4). The mean ratios of Fz to

 INSERT FIGURE 6 ABOUT HERE

to Pz were 0.96, 0.93, and 0.42 for the double-rare, the auditory-rare, and visual-rare $\overline{P300}$ s respectively. An analysis of variance on the base-to-peak amplitudes of the auditory and visual $\overline{P300}$ s showed a significant interaction between the effects of stimulus and electrode position ($p < 0.01$, $F(4,16) = 4.82$) while a similar analysis of the $\overline{P300}$ s to the same stimuli in Experiment II gave a non-significant interaction ($F(4,20) = 0.19$). This comparison is particularly meaningful in view of the fact that the topographical differences in Experiment III were found within the same series of stimulus presentations, while the identical distributions in Experiment II represent comparisons across blocks of trials.

Slow wave. The slow wave was measured, as before, as the mean difference in voltage from the pre-stimulus baseline to the last 150 msec of each waveform. These values are shown in Table 7. While the amplitudes and amplitude variations across electrodes differ somewhat across conditions, particularly for the auditory frequent-visual rare stimulus, the variations are unsystematic and do not correlate with the distributional variations of the $\overline{P300}$. Thus the distributional differences found for

the auditory and visual $\overline{P300}$ s cannot be attributed to variations in the slow wave elicited by the different stimuli. The distributional differences can be accounted for by the differential overlap of slow wave with the early and late $\overline{P300}$ s. Subjects with large slow waves and large latency differences between auditory and visual $\overline{P300}$ s also showed large distributional differences. Those with small slow waves and small latency differences had little or no distributional difference. The size of the

 INSERT TABLE 7 ABOUT HERE

distributional difference between the auditory and visual $\overline{P300}$ s (auditory Fz/Pz ratio minus the visual Fz/Pz ratio) had a 0.75 correlation with the size of the slow wave across the five subjects, and a correlation of 0.86 with the difference in the peak latencies of the auditory and visual $\overline{P300}$ s.

DISCUSSION

For a simplified comparison of the present data with traditional measures of bi-sensory interaction RTs to all stimuli in a condition were averaged for the relevant conditions of Experiment II and III (Table 3). As discussed previously, Experiment II

 INSERT TABLE 8 ABOUT HERE

showed a gain in performance with redundant dimensions (cf. cols. 1 and 11). In Experiment III dimensional interference was found in the filtering tasks (compare column iii, "filtering," with the corresponding unimodal results). Even greater interference was found in the condensation task (col. iii). While these effects are not large, they are comparable to the effects previously reported (e.g., Felfoldy, 1974; Garner, 1974).² Furthermore, interference between the dimensions in Experiment III can also be inferred from an analysis of the RTs to the individual types of rare events (Table 6). Irrelevant rare events delayed the "frequent" response and facilitated the "rare" response,

confirming that the "irrelevant" dimension was in fact not ignored. The ERP data also support this conclusion since the irrelevant rare stimuli did elicit a small $\overline{P300}$. By Garner's criteria then, the pitch and color dimensions used in these experiments would be considered "integral" dimensions. That this is the case with dimensions in two different sensory modalities is perhaps surprising. One possibility is that with further training the subjects might have been able to separate the dimensions more completely; however, the data of the two subjects who had already participated in the previous two experiments indicate that this is unlikely. Another important factor might be the difficulty of the discriminations involved; according to Long (1975), who used auditory frequency and visual intensity dimensions, interference is observed when the intra-modality discriminations are difficult, but no interference is observed with easy discriminations.³ A third possibility is that alternating between tasks, as was done here, interferes with the subjects' separation of the modalities. Whatever the explanation, it appears that the integrality concept must be interpreted more broadly than it has been previously. The close agreement found here between the physiological and performance data nevertheless supports the distinctions Garner has made about stimulus dimensions and also the utility of the $\overline{P300}$ component of the evoked response as a measure of these variables.

The RT data of Experiment III agree with those of Felfoldy (1974); the shortest RTs were to the double-frequent stimuli; a "rare" stimulus that required a "frequent" response (i.e., an irrelevant rare) produced some delay in RT, while a "rare" stimulus requiring a "rare" response (a relevant rare) delayed the response even further.⁴ The RT data, with those of Felfoldy, support the idea that reaction time reflects at least two stages of processing, evaluation of the stimulus and initiation of the appropriate motor response. On the other hand, the latency of $\overline{P300}$ did not vary with the counting response required. It is clear from Experiments I and II that $\overline{P300}$ latency can vary widely in counting tasks. There, $\overline{P300}$ latency varied with the discriminability of the relevant stimuli; the more difficult it was to identify the

stimuli, the later was the $\overline{P300}$. In Experiment III the discriminability of the two stimuli was constant, and so was the $\overline{P300}$ latency. So while there are evident differences between reaction time and counting tasks, the data of Experiments II and III, when taken together, present an instance in which an independent variable (stimulus discriminability) affects both $\overline{P300}$ latency and RT and another instance in which an independent variable (choice of target stimulus) affects reaction time and $\overline{P300}$ amplitude, but has no effect on $\overline{P300}$ latency. A plausible interpretation of these data is that the process manifested by $\overline{P300}$ is involved with stimulus evaluation rather than with response selection. Acceptance of this tentative conclusion must be tempered with caution pending a more direct comparison between the reaction time and counting tasks. A preliminary comparison, however, has been reported by Kutas and Donchin (in press), and their results are consistent with the present view.

The amplitude of the $\overline{P300}$, unlike its latency, did vary with the task in Experiment III. An irrelevant rare stimulus produced a small $\overline{P300}$, a rare stimulus in the relevant modality evoked a larger $\overline{P300}$, and the largest $\overline{P300}$ was associated with the double-rare stimuli. Thus $\overline{P300}$ amplitude appears to increase with the discrepancy between the stimulus expected (the double-frequent) and that which actually occurs. This effect has been called "equivocation" by Ruchkin and Sutton (in press) and has been supported by several investigations (e.g., Adams and Benson, 1973; Ford, Roth and Kopell, 1976; Hillyard, Squires, K., and Squires, N., note 1; Johnson and Donchin, note 2).

The scalp distribution of $\overline{P300}$ varied in yet a third manner; auditory rare and double-rare stimuli both evoked $\overline{P300}$ s that were basically equipotential over Pz, Cz, and Fz, while the $\overline{P300}$ s to the visual-rare stimuli were larger at Pz than Fz. These relationships were independent of the counting condition. This result is of particular importance in view of the recent trend in the $\overline{P300}$ literature to identify a variety of different kinds of " $\overline{P300}$ s" mainly on the basis of their different scalp topographies (see Tueting, in press, for a discussion of this trend). While we have tentatively attributed the effect reported here to the differential overlap of $\overline{P300}$ and slow wave,

it is certainly not clear at this point whether such an explanation would account for other reported differences in scalp topography, for example those of Courchesne, Hillyard, and Galambos (1975) who reported that novel, irrelevant visual stimuli inserted into a Bernoulli series of visual stimuli elicited a $\overline{P300}$ with a frontal distribution, while the relevant rare targets elicited a $\overline{P300}$ with a more parietal distribution.

Since it appears that speed measures of information processing provide a combined measure of several stages of processing, while $\overline{P300}$ is influenced by only a particular subset of those variables, $\overline{P300}$ emerges as a useful adjunct to more traditional means of evaluating cognitive events. This is particularly true in that $\overline{P300}$ appears to be a multifaceted index whose various characteristics are functionally independent. $\overline{P300}$ latency reflects the discriminability of stimuli along the relevant dimension and presumably the speed of identification and decision making (Experiments I and II); $\overline{P300}$ amplitude increases when the jitter in its latency is reduced (Experiment II; Ruchkin and Sutton, in press) and with increased discrepancy between what is expected and what occurs (Experiment III); and finally $\overline{P300}$ scalp distribution also varies with differences in processing, although the nature of this variation is as yet not well defined. While the functional and neurophysiological nature of $\overline{P300}$ and other ERP components remain to be determined, the experiments reported here affirm their status as important indices of cognitive processes, and perhaps more importantly emphasize the multifaceted nature of $\overline{P300}$ and the independence of its various characteristics.

FOOTNOTES

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²Also, this method of data presentation probably underestimates the amount of facilitation or interference compared to more traditional measures due to the use of asymmetric probabilities of the various stimuli. Felfoldy (1974) found that the largest effect of going from one variable dimension to two was on the RTs to non-repetitions of stimuli. In that the use of asymmetric probabilities produces fewer non-repetitions, the averaged effect would be diminished.

³Long's measure of interference was a decrease in the percent correct. With easy discriminations performance may be asymptotically 100% correct, and interactions between the dimensions may be obscured. Thus the relevance of this variable for other types of measures is not yet clear.

⁴Felfoldy performed a trial-by-trial analysis of his data, looking at the effects of repetitions and non-repetitions of the stimulus and response conditions from the last trial. Thus the analysis is not directly comparable to the one performed here. However, with the probabilities used in Experiment III, it can be safely assumed that the "double-frequent" stimuli mainly represent repetitions of stimuli and responses, and that the rare stimuli represent non-repetitions of stimuli, and either repetitions or non-repetitions of responses, depending on the particular condition, so that by and large the comparison between the results of the two experiments is straightforward.

REFERENCES

- Adams, J., & Benson, D. Task-contingent enhancement of the auditory evoked response. Electroencephalography and Clinical Neurophysiology, 1973, 35, 249-257.
- Biederman, I., & Checkosky, S. Processing redundant information. Journal of Experimental Psychology, 1970, 83, 486-490.
- Colavita, F. Human sensory dominance. Perception and Psychophysics, 1974, 16, 409-412.
- Courchesne, E., Hillyard, S., & Galambos, R. Stimulus novelty, task relevance and the visual evoked potential in man. Electroencephalography and Clinical Neurophysiology, in press.
- Donchin, E. Brain electrical correlates of pattern recognition. In Inbar, G. (Ed.), Signal Analysis and Pattern Recognition in Biomedical Engineering, John Wiley, 1975, 199-218.
- Donchin, E., & Heffley, E. Using minicomputers in the signal averaging laboratory. American Psychologist, 1975, 30, 299-312.
- Donchin, E., & Sutton, S. The "psychological significance" of evoked responses: A comment on Clark, Butler and Rosner. Communications in Behavioral Biology, 1970, 5, 111-114.
- Donchin, E., Kubovy, M., Kutas, M., Johnson, R., Jr., & Herning, R. Graded changes in evoked response (P300) amplitude as a function of cognitive activity. Perception and Psychophysics, 1973, 14, 319-324.
- Falmagne, J. C., Cohen, S. P., & Dwivedi, A. Two choice reactions as an ordered memory scanning process. In P. M. A. Rabbitt and S. Dornic (Eds.), Attention and Performance, V., Academic Press, New York, 1975.
- Felfoldy, G. Repetition effects in choice reaction time to multidimensional stimuli. Perception and Psychophysics, 1974, 15, 453-459.
- Ford, J., Roth, W., & Kopell, B. Auditory evoked potentials to unpredictable shifts in pitch. Psychophysiology, 1976, 13, 32-39.

- Garner, W. The processing of information and structure, New York: John Wiley and Sons, 1974.
- Garner, W., & Felfoldy, G. Integrality of stimulus dimensions in various types of information processing. Cognitive Psychology, 1970, 1, 225-241.
- Gottwald, R., & Garner, W. Filtering and condensation tasks with integral and separable dimensions. Perception and Psychophysics, 1975, 18, 26-28.
- Hershenson, M. Reaction time as a measure of intersensory facilitation. Journal of Experimental Psychology, 1962, 63, 289-293.
- Jenness, D. Auditory evoked-response differentiation with discrimination learning in humans. Journal of Comparative and Physiological Psychology, 1972, 80, 75-90.
- Karlin, L., & Martz, M. Response probability and sensory evoked potentials, motor potentials, and reaction time. In S. Kornblum (Ed.), Attention and performance, IV, New York: Academic Press, 1973.
- Kornhuber, H., & Deecke, L. Hirnpotential - anderungen bei Willkurbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotential und reafferent potential. Pflugers Archives, 1965, 284, 1-17.
- Kutas, M., & Donchin, E. Variations in the latency of P300 as a function of variations in semantic categorization. In D. Otto (Ed.), Proceedings of the 4th International Congress on Event Related Slow Potentials of the Brain, in press.
- Long, J. Reduced efficiency and capacity limitations in multidimensional signal recognition. Quarterly Journal of Experimental Psychology, 1975, 27, 599-614.
- Loveless, N., Brebner, J., & Hamilton, P. Bisensory presentation of information. Psychological Bulletin, 1970, 73, 161-199.
- Picton, T., Hillyard, S., & Galambos, R. Cortical evoked responses to omitted stimuli. In Livanov, M. N. (Ed.), Major Problems in Brain Electrophysiology, USSR: Academy of Sciences, 1974.
- Posner, M. Information reduction in the analysis of sequential tasks. Psychological Review, 1964, 71, 491-504.
- Price, R., & Smith, D. B. D. The $P_{3(00)}$ wave of the averaged evoked potential: A

- bibliography. Physiological Psychology, 1974, 2, 387-391.
- Raab, D. Statistical facilitation of simple reaction times. Transactions of the New York Academy of Sciences, 1962, Ser. 5, 24, 574-590.
- Remington, R. J. Analysis of sequential effects in choice reaction times. Journal of Experimental Psychology, 1969, 2, 250-257.
- Ritter, W., & Vaughan, Jr., H. G. Average evoked responses in vigilance and discrimination: A reassessment. Science, 1969, 164, 326-328.
- Ritter, W., Simson, R., & Vaughan, Jr., H. G. Association cortex potentials and reaction time in auditory discrimination. Electroencephalography and Clinical Neurophysiology, 1972, 33, 547-555.
- Rohrbaugh, J., Donchin, E., & Eriksen, C. Decision making and the P300 component of the cortical evoked response. Perception and Psychophysics, 1974, 15, 368-374.
- Ruchkin, D., & Sutton, S. Visual evoked and emitted potentials and stimulus significance. Bulletin of the Psychonomic Society, 1973, 2, 144-146.
- Ruchkin, D., & Sutton, S. Equivocation and P300 amplitude. In D. Otto (Ed.), Proceedings of the Fourth International Congress on Event Related Slow Potentials of the Brain, in press.
- Squires, K., Hillyard, S., & Lindsay, P. Cortical potentials evoked by confirming and disconfirming feedback following an auditory discrimination. Perception and Psychophysics, 1973, 13, 25-31.
- Squires, K., Donchin, E., Herning, R., & McCarthy, G. On the influence of task relevance and stimulus probability on ERP components. Electroencephalography and Clinical Neurophysiology, in press.
- Squires, K., Wickens, C., Squires, N., & Donchin, E. The effect of stimulus sequence on the waveform of the cortical event-related potential. Science, in press.
- Squires, N., Squires, K., & Hillyard, S. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. Electroencephalography and Clinical Neurophysiology, 1975, 38, 387-401.
- Thatcher, R. Evoked potential correlates of hemispheric lateralization during semantic

- information processing. In S. Harnad et al. (Eds.), Lateralization in the Nervous System. New York: Academic Press, in press.
- Thurmond, J. B., & Alluisi, E. A. Choice time as a function of stimulus dissimilarity and discriminability. Canadian Journal of Psychology, 1963, 17, 326-337.
- Tueting, P. Event-related potentials, cognitive events, and information processing. In D. Otto (Ed.), Proceedings of the Fourth International Congress on Event Related Slow Potentials of the Brain. In press.
- Tueting, P., Sutton, S., & Zubin, J. Quantitative evoked potential correlates of the probability of events. Psychophysiology, 1971, 7, 385-394.
- Wilkinson, R., & Spence, M. Determinants of the post-stimulus resolution of contingent negative variation (CNV). Electroencephalography and Clinical Neurophysiology, 1973, 35, 503-509.
- Wood, C. Parallel processing of auditory and phonetic information in speech perception. Perception and Psychophysics, 1974, 15, 501-508.
- Wood, C. A normative model for redundancy gains in speech discrimination. In F. Restle, R. M. Shiffrin, N. J. Castellan, H. Lindman, and D. B. Pisoni (Eds.), Cognitive Theory: Volume I. Erlbaum Assoc., Potomac, Md., 1975.

REFERENCE NOTES

¹Hillyard, S., Squires, K., & Squires, N. Evoked potential correlates of attention. For Carterette, E. and Friedman, M. (Eds.), Handbook of Perception, Hearing, in preparation.

²Johnson, Jr., R., & Donchin, E. Intensity discrimination effects on the auditory event related potential, in preparation.

TABLE 1: Scalp-amplitude distributions of the $\overline{P300}$ component, associated with rare unimodal and bimodal events in μ volts. Means of six subjects.

	Oz	Pz	Cz	Fz	FPz
a) Auditory rare	12	23	21	17	5
b) Visual rare	17	34	31	14	2
c) Auditory rare- visual frequent	17	27	22	14	1
d) Visual rare- Auditory frequent	16	31	25	14	3
e) Auditory rare- visual rare	18	32	26	18	4

TABLE 2: Reaction times to rare and frequent stimuli in all eight conditions of Experiment II. Means of seven subjects.

	FREQUENT		RARE	
	Mean	S.D.	Mean	S.D.
Easy Auditory	279	43	387	68
Difficult Auditory	374	66	532	101
Easy Visual	276	28	392	56
Difficult Visual	340	82	446	68
Easy Auditory-Easy Visual	251	41	366	53
Easy Auditory-Difficult Visual	260	32	384	67
Difficult Auditory-Easy Visual	261	32	391	56
Difficult Auditory-Difficult Visual	294	34	424	66

TABLE 3: Latencies of the P300s to the rare stimulus in each of the eight conditions of Experiment II. Means of six subjects.

	<u>P300 Latency</u>	
	<u>Mean</u>	<u>S.D.</u>
Easy Auditory	359	41
Difficult Auditory	419	52
Easy Visual	371	18
Difficult Visual	420	16
Easy Auditory-Easy Visual	349	35
Easy Auditory-Difficult Visual	362	34
Difficult Auditory-Easy Visual	370	16
Difficult Auditory-Difficult Visual	403	34

TABLE 4: Amplitude (μv) of the slow wave evoked by the rare stimulus in each of the eight conditions of Experiment II, for the five electrode locations. Mean of six subjects.

<u>Condition:</u>	<u>Electrode</u>				
	<u>Oz</u>	<u>Pz</u>	<u>Cz</u>	<u>Fz</u>	<u>FPz</u>
Auditory Easy	9	12	1	-14	-17
Auditory Difficult	4	9	1	- 8	-12
Visual Easy	7	10	1	-12	-17
Visual Difficult	3	13	5	- 8	-12
Auditory Easy-Visual Easy	4	6	-2	-14	-18
Auditory Easy-Visual Difficult	6	9	-2	-14	-17
Auditory Difficult-Visual Easy	3	7	-1	-16	-20
Auditory Difficult-Visual Difficult	9	14	5	-13	-14

TABLE 5: Mean $\overline{P300}$ latencies and amplitudes (Cz) for the three experimental conditions for the three types of rare stimuli.

P300 Latencies:

		STIMULUS		
		Auditory rare- visual rare	Auditory rare- visual frequent	Auditory frequent- visual rare
COUNT	Mean:	356	354	400
AUDITORY	S.D.	(15)	(19)	(23)
COUNT	Mean:	350	356	394
VISUAL	S.D.	(20)	(38)	(23)
COUNT	Mean:	352	351	398
BOTH	S.D.	(17)	(23)	(23)

P300 Amplitudes:

COUNT	Mean:	25	18	5
AUDITORY	S.D.	(10)	(6)	(3)
COUNT	Mean:	23	11	13
VISUAL	S.D.	(4)	(2)	(4)
COUNT	Mean:	24	14	10
BOTH	S.D.	(7)	(4)	(6)

TABLE 6: mean reaction times to rare and frequent stimuli for the seven subjects in Experiment III.

ATTEND:		AUDITORY: VISUAL:	rare	rare frequent	frequent rare	frequent frequent
AUDITORY:	Mean		401	426	340	298
	S.D.		67	69	80	40
VISUAL:	Mean		384	342	399	276
	S.D.		55	62	60	24
BOTH:	Mean		409	485	467	317
	S.D.		69	90	99	42

Table 7: Amplitude (μv) of the slow wave evoked by each of the three types of rare stimuli in each experimental condition of Experiment III.
Mean of five subjects.

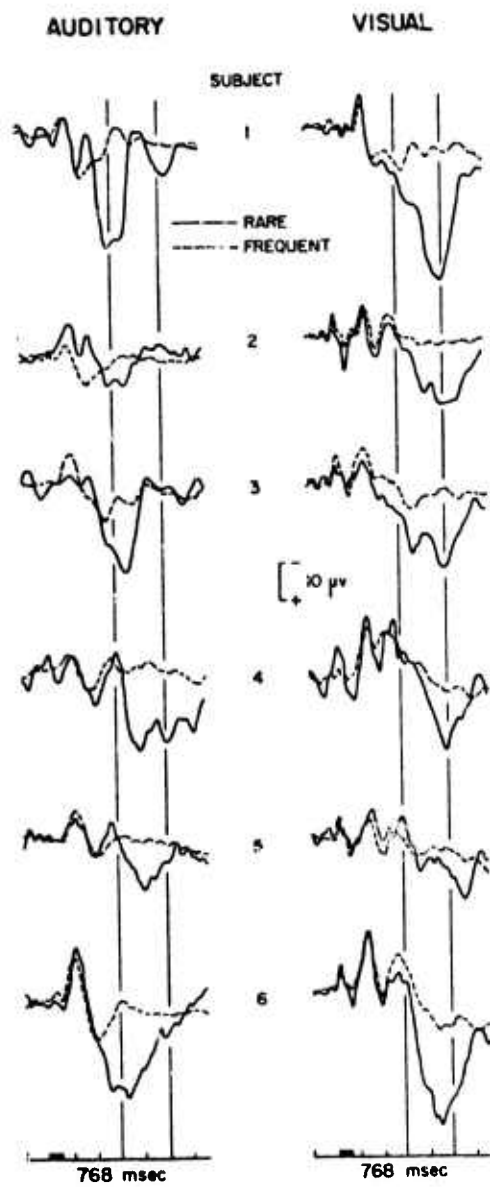
<u>Eliciting Stimulus:</u>	<u>Counted Stimulus:</u>	<u>Electrode:</u>				
		<u>Oz</u>	<u>Pz</u>	<u>Cz</u>	<u>Fz</u>	<u>FPz</u>
Auditory rare- Visual rare	Auditory	6.2	5.9	0.0	-5.4	-6.5
	Visual	4.5	1.8	-3.5	-9.0	-7.7
	Both	5.2	2.8	-1.0	-5.0	-1.0
Auditory rare- Visual frequent	Auditory	2.4	3.4	-2.8	-7.8	-11.2
	Visual	2.6	2.6	-0.2	-4.8	-7.1
	Both	5.1	6.2	0.4	-5.8	-9.6
Auditory frequent- Visual rare	Auditory	1.5	4.5	2.6	-0.2	-4.2
	Visual	1.6	2.7	-5.1	-12.3	-13.4
	Both	6.2	7.6	2.0	-3.9	-8.8

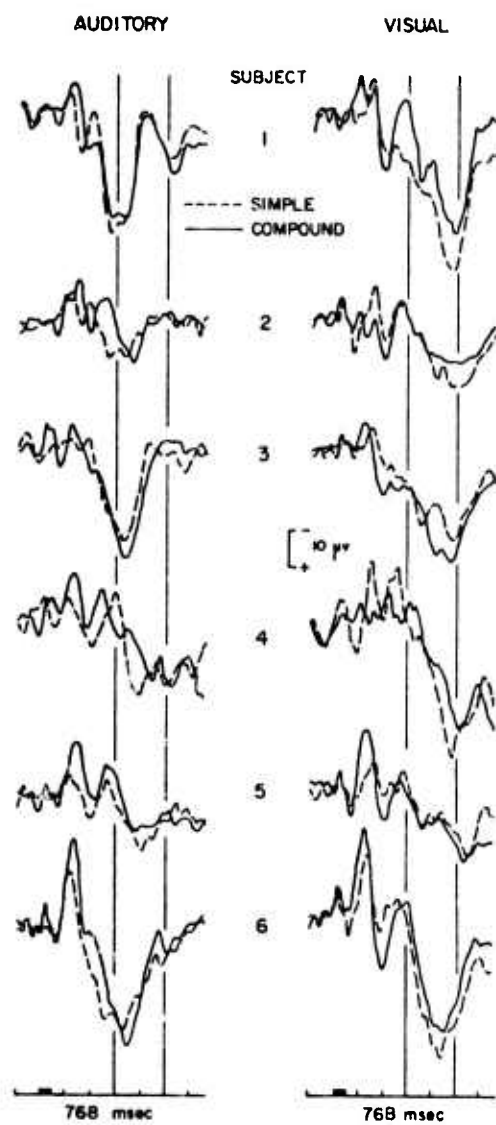
TABLE 8: Mean RTs in unimodal auditory easy and visual easy conditions (Experiment II), the redundant compounds (auditory easy - visual easy, Experiment II), and the non-redundant compounds under different instructional conditions (Experiment III).

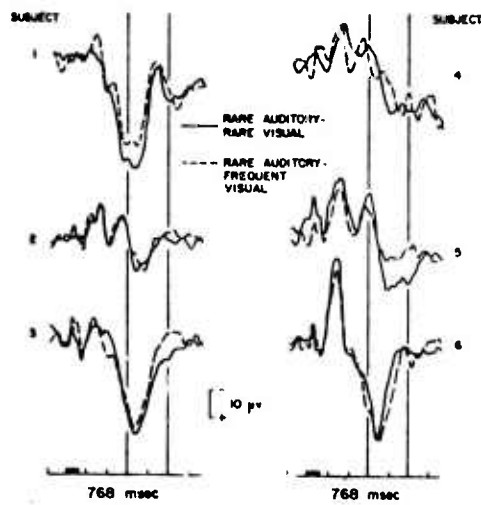
<u>TASK</u>	<u>STIMULI</u>		
	i. <u>Unimodal</u>	ii. <u>Redundant</u>	iii. <u>Non-Redundant</u>
AUDITORY	290 (II)	_____	312 (III-filtering)
VISUAL	288 (II)	_____	291 (III-filtering)
AUDITORY-VISUAL	_____	262 (II)	338 (III-condensation)

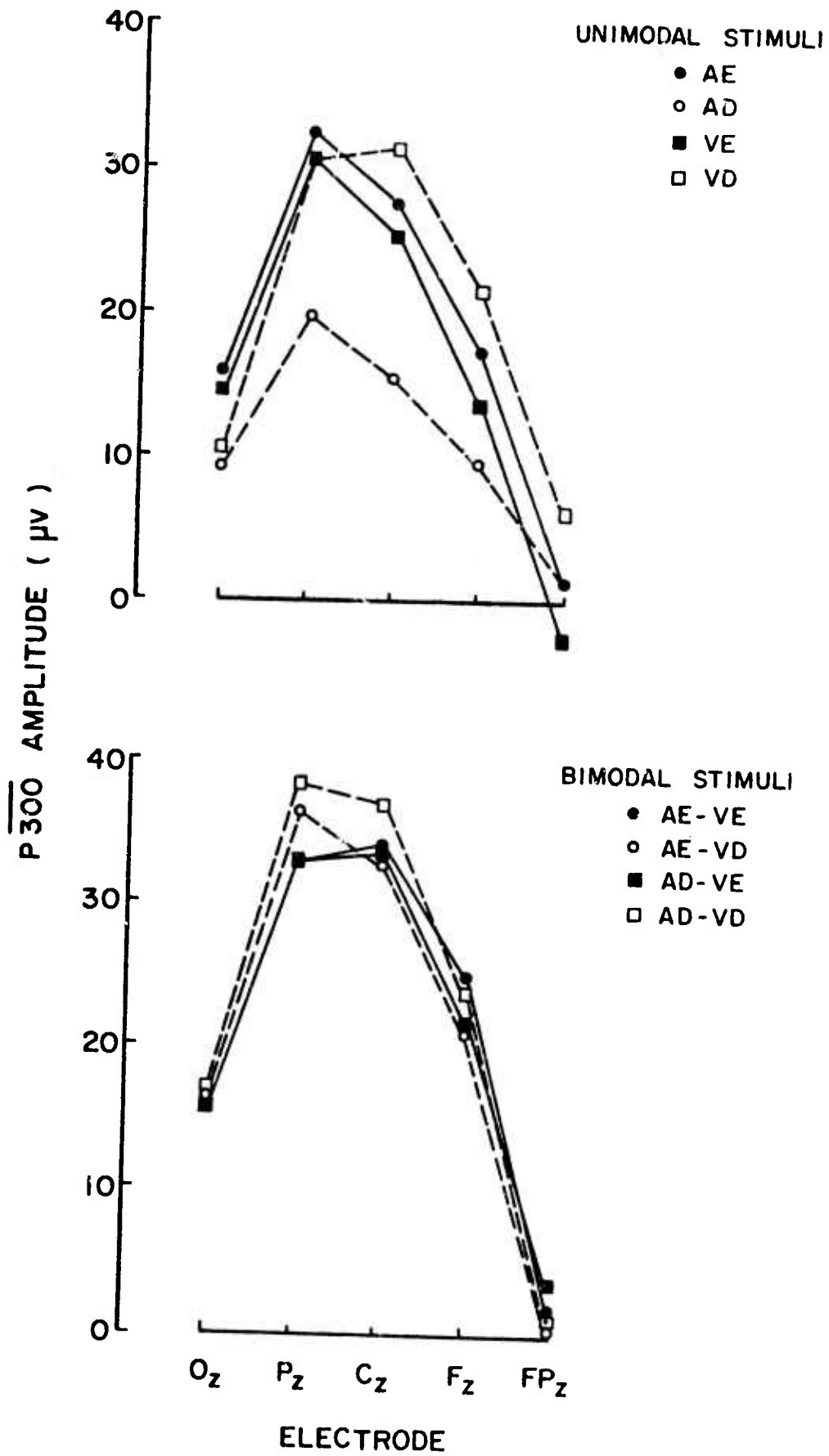
FIGURE LEGENDS

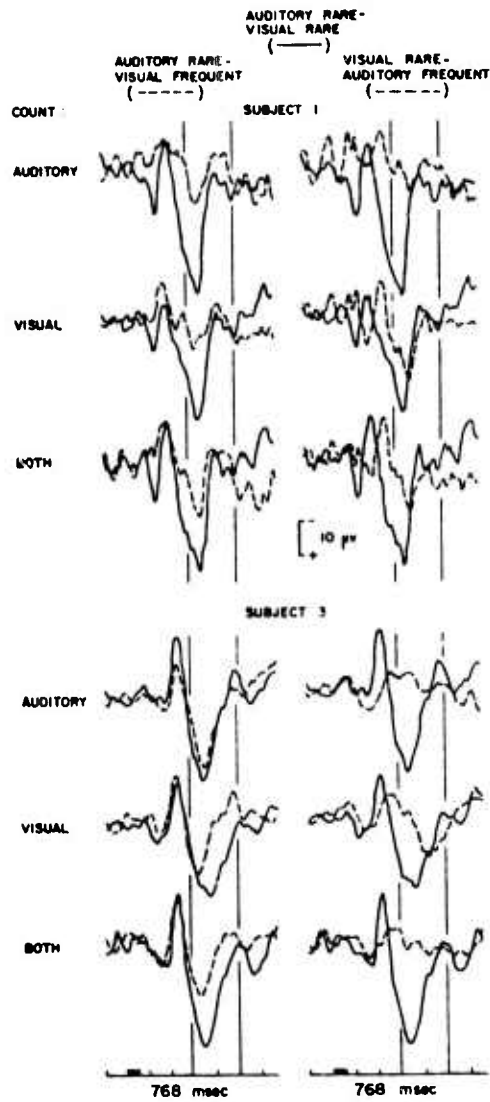
- Figure 1: Experiment I: Vertex evoked responses to the unimodal stimuli for each of the six subjects. The responses to the rare stimuli (solid lines) are superimposed on the responses to the frequent stimuli (dotted lines) from the same condition.
- Figure 2: Each subject's vertex evoked responses to the unimodal auditory and visual rare stimuli (solid lines) superimposed on the response evoked by that same stimulus when accompanied by a frequent stimulus in the other modality.
- Figure 3: Vertex evoked responses to the rare auditory-rare visual compound (solid line) superimposed on the response to the rare auditory-frequent visual stimulus (dotted line) for each of the six subjects.
- Figure 4: Experiment II: Mean baseline-to-peak amplitude of $\overline{P300}$ at each of the five electrode sites, for each of the eight experimental conditions. (Abbreviations, auditory easy - AE, auditory difficult - AD, visual easy - VE, visual difficult - VD.)
- Figure 5: Experiment III: Subtracted waveforms of two subjects for double (solid lines) and single (dotted lines) rares for each counting condition. The ERP to the double rare (auditory rare-visual rare) is shown once in the left column superimposed on the response to the auditory rare-visual frequent stimulus, and once on the right superimposed on the response to the visual rare-auditory frequent stimulus.
- Figure 6: Mean $\overline{P300}$ scalp-amplitude distribution for each stimulus in each counting condition.

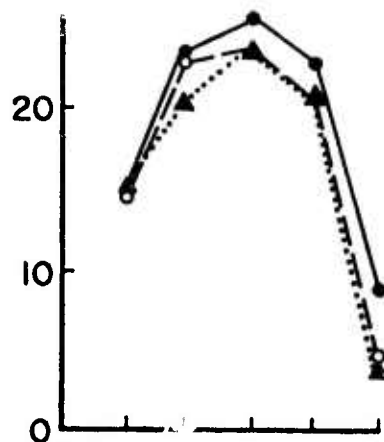
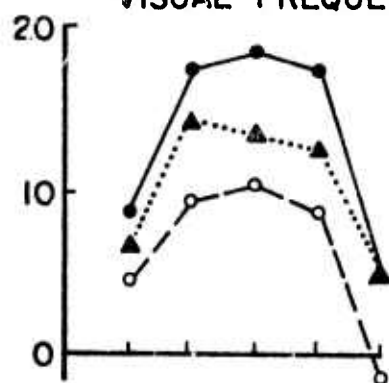






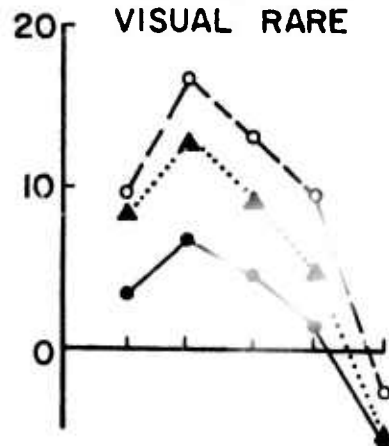




AUDITORY RARE-
VISUAL RAREAUDITORY RARE-
VISUAL FREQUENT

COUNTED :

- AUDITORY
- VISUAL
- ▲ BOTH

AUDITORY FREQUENT-
VISUAL RAREO₂ P_z C_z F_z FP_z

ELECTRODE

P300 AMPLITUDE (µV)

THE EFFECTS OF TEMPORAL AND EVENT UNCERTAINTY IN DETERMINING THE
WAVEFORMS OF THE AUDITORY EVENT RELATED POTENTIAL (ERP)

Gregory McCarthy and Emanuel Donchin

Department of Psychology

University of Illinois

Champaign, Illinois 61820

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Running title: Self Stimulation and ERPs

Send Proofs to:

Emanuel Donchin

Department of Psychology

University of Illinois

Champaign, Illinois 61820

Abstract

In each of two experimental conditions, subjects were presented with a series of tones; one of two tones (1500 Hz or 1000 Hz) was presented on each trial with a probability respectively of .10 or .90. The subjects counted the rare ($p = .10$) tones; such counted rare tones are normally associated with a large P_{300} component.

The two conditions differed in that in one the tones were triggered by the subject's button press; in the other the tones were triggered by computer. Schafer & Marcus (1973) reported that all the components of event-related potentials (ERPs) elicited by self-triggered tones were substantially smaller than those elicited by machine-triggered stimuli. Our paradigm allowed a detailed assessment of the effects of self-stimulation on specific ERP components as well as the interaction of temporal with event uncertainty.

Data were analyzed using a Principal Components technique. Both temporal and event uncertainty appeared to augment a negative component of the ERP with approximately 140 msec latency. Such effects, however, were confounded by the presence of slow negative potentials preceding the button press in the self-stimulation conditions. As expected, the P_{300} component was largest for the ERPs elicited by the rare tones. Temporal uncertainty diminished the amplitude of P_{300} at central electrode sites. A large slow wave was present following P_{300} ; its anterior-posterior distribution was altered by mode of stimulus presentation. It appears that temporal and event uncertainty have distinct effects upon the morphology and distribution of ERP components.

Descriptors: P_{300} , auditory evoked potentials, temporal and event uncertainty.

Schafer and Marcus (1973) reported differences in the waveforms of auditory and visual event-related potentials (ERP) as a function of the manner in which the eliciting stimuli were triggered. Specifically, the ERPs elicited by subject-initiated stimuli were considerably smaller (and with shorter latency components) than ERPs elicited by the same stimuli triggered by machine. Schafer and Marcus reported that all components of the ERP whose latencies exceed 100 msec, including the P_{300} component, were larger in the ERPs elicited by the machine-triggered stimuli.

The two modes of triggering differ in at least two ways: (1) a motor response is required when the subject triggers each stimulus, and (2) the subject cannot know with certainty when the machine-triggered stimulus will appear. Schafer and Marcus attribute the enhancement of the ERP components elicited by the machine-triggered stimuli to the temporal uncertainty. Effects related to the temporal characteristics of stimulus sequences have been previously reported for ERP components with latencies between 80 and 250 msec (Davis, Mast, Yoshie, & Zerlin, 1966; Rothman, Davis, & Hay, 1970; Lentonen, 1973). However, no such data have been previously reported for the P_{300} component.

The appearance of the P_{300} component in the averaged ERP has been linked to stimulus uncertainty (Sutton, Braren, Zubin, & John, 1965; Donchin, 1968). However, in such studies the uncertainty was as to which stimulus would occur (see Donchin & Cohen, 1967 for an exception). In the Schafer and Marcus paradigm, however, the stimulus was always the same, in question was its time of occurrence.

There is ample evidence that the task relevance or information value of the eliciting stimulus is crucial for the appearance of P_{300} (Donchin, 1975). As there were no experimenter-directed tasks in the Schafer and Marcus experiment, one might conclude from their data that temporal uncertainty is sufficient for the elicitation of P_{300} . Such an interpretation gains support from Ford, Roth, & Kopell (1976) who suggested that "the well known influence of stimulus uncertainty on P_{300} may be determined by the temporal rather than sequential uncertainty of events."

In light of the theoretical implications of such inferences, we initiated a replication and extension of the "self-stimulation" paradigm in which both temporal and event uncertainty were independently manipulated. To insure the elicitation of a P_{300} , series of Bernoulli trials were used in which the two possible stimuli presented on each trial had probabilities of .10 and .90. It is well known that if the rare stimuli, in this "oddball" paradigm are made task relevant by requiring the subjects to count their occurrence, a large P_{300} appears in the ERP elicited by the rare stimuli (Squires, Squires, & Hillyard, 1975; Squires, Donchin, Herning, & McCarthy, in press). Thus our design allows an examination of the effects of both temporal and event uncertainty, as well as their interaction, on the waveform of the ERP.

METHODS

Subjects. Eight young adults (5 female, 3 male) participated in the study. Four of the subjects, including experimenter GM, had prior experience in ERP experiments.

Stimuli. Tone bursts of either 1000 Hz or 1500 Hz (both at 93 dB SPL), presented against a white noise background (60 dB SPL), were delivered binaurally through TDH-39 earphones. Each tone had a total duration of 15 msec (5 msec rise-time, 5 msec fall-time and 5 msec steady level). The rather high intensity tones and background noise were necessary to mask the audible operation of the microswitch used in the self-triggering conditions.

Recording System. The EEG was recorded from nine Burden Ag-AgCl electrodes (F_3 , F_z , F_4 , C_3 , C_z , C_4 , P_3 , P_z , P_4 --according to the 10-20 system), each referred to linked mastoids. In addition, Beckman Ag-AgCl electrodes were placed above and below the right eye to record the electro-oculogram (EOG). In seven subjects, the ground electrode was placed on the chin, while in one subject it was placed on the left wrist. Grass 7P122 amplifiers were used to record both the EEG and EOG. The bandpass was 0.2 Hz to 35 Hz (1/2 amplitude cutoff).

Data Collection. All aspects of data collection and experimental control were managed by a PDP-11/40 computer system (Donchin & Heffley, 1975). The ten channels of data (nine EEG and one EOG channel) were digitized, sorted, and averaged on-line. For all conditions except the ODD condition (see below), the data were digitized at 10 msec/point for a 2000 msec epoch beginning 1000 msec prior to stimulus presentation. In the ODD condition, the data were digitized at 4 msec/point for a total of 800 msec beginning 200 msec prior to the stimulus. Eye movements were detected on-line by a voltage-window algorithm; trials in which EOG artifacts occurred were not used in the computation of the averaged ERPs.

Both single trials and averages were stored on magnetic tape for off-line analysis on the IBM 360/75 of the Computer Services Office of the University of Illinois. All statistical analyses were performed using the SOUPAC statistical package (Dickman, 1974).

Procedure. The subject was seated in a reclining chair in a dimly lighted booth. Each session, typically lasting 2 1/2 hours, contained the following conditions. The first two conditions are similar to those used by Schafer and Marcus (1973).

1. Self-Stimulation (SSTM). In this condition the subjects pressed a microswitch with the index finger of their right hand at intervals of their choosing. Subjects were cautioned against responding more frequently than once every 1500 msec. Each switch closure immediately triggered a 1000 Hz tone. Fifty (50) tones were presented in each SSTM run. The intervals between successive stimuli were recorded.

2. Machine Stimulation (MACH). A series of 50 tones, each of 1000 Hz, were presented to the subject. These tones were triggered by the computer using intervals between successive stimuli generated by the subject in the immediately preceding SSTM condition.

The following two conditions, designed to assure the elicitation of a P300 component, represent an extension of the Schafer and Marcus paradigm.

3. Self-Stimulation-Oddball (SSTM-ODD). This condition was identical to the SSTM condition except that each switch closure triggered either a 1000 Hz tone or a 1500 Hz tone. The probability that a high pitch tone would be triggered was $P = .10$; low pitch tones were triggered with a probability $P = .90$. Subjects initiated 200 such trials and were instructed to count the rare, high pitched, tones and report their count at the end of a block.

4. Machine Stimulation-Oddball (MACH-ODD). A series of 200 tones were triggered by the computer at the intervals generated by the subject in the immediately preceding SSTM-ODD condition. Tone probabilities were the same as in SSTM-ODD condition and the subject was again instructed to count the rare, high pitched tones.

Two additional conditions were used:

4. Control (CONT). To allow an assessment of the contribution of movement related potentials to the SSTM data, subjects pressed the microswitch at their own rate. No stimuli were triggered.

6. Oddball (ODD). To allow comparison with similar studies of P300 a series of 200 tones ($P(1000 \text{ Hz}) = .90$; $P(1500 \text{ Hz}) = .10$), were triggered by the computer. The interstimulus interval was fixed at 1600 msec.

With the constraint that machine-triggered series followed the corresponding self-triggered series, the order of experimental conditions was balanced over the subjects.

RESULTS

The mean ISIs associated with the SSTM and SSTM-ODD conditions (and, consequently, with the MACH and MACH-ODD conditions) varied among subjects from 3400 msec (standard deviation (sd) = 911 msec) to 9789 msec (sd = 1881 msec) for the SSTM-ODD conditions and from 4140 msec (sd = 1104 msec) to 8634 msec (sd = 1575 msec) for SSTM. Within subjects, ISIs for SSTM and SSTM-ODD were quite similar; deviating at most by 1155 msec.

ERP Waveforms. A summary of the data is presented in Figure 1 where waveforms averaged across subjects for each experimental condition ("grand-averages") are shown (data from a typical subject are displayed in Figure 2). The data acquired in the ODD condition replicate in all respects data acquired in other laboratories (Ritter, Vaughan, & Costa, 1968; Squires, N. et al., 1975) as well as in our own (Squires, K. et al., in press). A large P_{300} component is associated with the counted rare tones, and is absent in the frequent tone ERP.

A comparison of the waveforms from the SSTM and MACH conditions (which differed only in the mode of stimulus initiation) revealed that the negative peak with a latency of approximately 140 msec (N_{140}) was enhanced in the MACH condition. This effect was largest centrally, smaller at the frontal electrodes, and smallest at the parietal electrodes. This negative peak and the following positive trough also appeared with a somewhat shorter latency in the SSTM condition.

A more complex ERP waveform was associated with the SSTM-ODD and MACH-ODD conditions. Again, the N_{140} associated with the MACH-ODD condition was larger than the corresponding peak in the SSTM-ODD condition; this effect occurring primarily at C_z and F_z . Again, a latency difference was observed with earlier latencies apparent in the SSTM-ODD waveforms. As in the ODD waveforms, a

Figs. 1
and 2

prominent P_{300} component was associated with the counted rare tones. This is most clearly seen at P_z where (except for latency differences) the ERPs to the self-triggered and machine-triggered tones were nearly identical. At C_z however, the MACH-ODD and SSTM-ODD waveforms were quite dissimilar, the prominent P_{300} which can be observed in the SSTM-ODD waveform was not present in the MACH-ODD waveform.

The data elicited during the CONT condition in which no auditory stimulus was presented may be used to assess the extent to which the switch-depression may account for the differences between the SSTM and MACH data. The records exhibit considerable post-movement positive activity and, at C_z , a small amplitude premovement negative shift can be seen. These data suggest that the ERPs recorded in each of the self-triggered conditions may have been "contaminated" by movement-related potentials; the CONT waveforms were, therefore, subtracted point-by-point from both the SSTM and SSTM-ODD waveforms. In Figure 3 MACH with SSTM ERPs are compared both before and after subtraction of the CONT waveforms from the SSTM waveforms. The latency differences between SSTM and MACH ERPs which appear in the left column disappear after the movement-related potentials were subtracted from the SSTM ERPs. It should be noted that after the removal of motor potentials, the SSTM ERPs virtually disappear. It seems, therefore, that little, if any, stimulus evoked activity was recorded in the SSTM condition.

Note also the partial restoration of N_{140} amplitude in the SSTM-ODD waveforms after subtraction. This effect is most apparent for the waveforms elicited by the frequent tones where N_{140} amplitudes are nearly identical at C_z for both MACH-ODD and SSTM-ODD. ERPs elicited by the rare tones, however, still differ in N_{140} amplitude with MACH-ODD waveforms displaying larger amplitude.

Principal Component Analysis. The above impressions were derived by visual inspection of the averaged waveforms. To quantify and further evaluate the effects of the independent variables on the different components of the ERP, a Principal Component Analysis (PCA) of the waveform data was performed. The application of this multivariate analysis technique to ERP data has been treated by Donchin (1966, 1969) and illustrated by Donchin, Tueting, Ritter, Kutas, and Heffley (1975) and Squires, K. et al. (in press). A PCA of a data set yields two major results--a statement about the orthogonal components into which the data matrix can be factored and a measure of the contribution of each of the principal components to each of the ERPs.

For each of the principal components a set of "factor-loadings" is obtained. There is a loading for each component per time point of the recording epoch. The loading is a measure of the degree of association between the hypothetical component and the time point. The principal components represent the ERP components which appear in the time segment in which the factor is highly loaded. The contribution of a component to an ERP waveform is measured by the "factor-scores," which are analogous to the base-to-peak component measures which are often used in ERP studies (see Squires, K. et al. for a discussion of this issue). The factor-scores have the advantage inter alia that a separate analysis of variance can be performed on the scores obtained for each component.

Two separate PCA were conducted, one on data obtained in the SSTM and MACH conditions and one on the SSTM-CDD and MACH-ODD conditions. The input to the PCA in each case was the cross-products matrix formed by obtaining the cross-products of the voltage values at all possible pairs of time points (thus the element in the i-th row and j-th column of the matrix is obtained by multiplying the values at the i-th and j-th time-point in each ERP and

summing the products). The variance accounted for by the first 6 factors was 84% in the SSTM/MACH PCA and 85% in the SSTM-ODD/MACH-ODD PCA. Each set of components was rotated using the Varimax procedure, and the loadings for both analyses are plotted in Figure 4.

It is clear from Figure 4 that the extracted components correspond to each of the major ERP components discussed in conjunction with the Grand-Averages. The two PCAs differ primarily in that a component whose maximal loadings appear 380 msec after the stimulus is extracted from the SSTM-ODD/MACH-ODD analysis but not in the SSTM/MACH analysis. In both analyses two factors are extracted with maximal loadings at 140 msec and 200 msec, and two with fairly broad ranges; one covering the epoch just preceding the stimulus and the other covering the period from about 500 msec after the stimulus to the end of the analysis epoch.

The extracted components are best interpreted by referring to the behavior of the factor-scores as a function of the various experimental variables. For the purposes of this analysis we view the experimental design as a repeated measures factorial design. In the SSTM/MACH data the factors are the electrodes and the mode of stimulus presentation. For the SSTM-ODD/MACH-ODD matrix the stimulus type (rare vs. frequent) is added. This, in fact, was the rationale for the separate analyses of these data-sets.

The results for the several factors can be summarized as follows:¹

Component I from the SSTM/MACH analysis can be identified with the N140 component of the ERP. It is largest at C_z ($F(8/56) = 2.67$, $MS_e = 0.001$) with a sharp posterior gradient. It is significantly affected by mode of stimulus presentation ($F(1/7) = 10.34$, $MS_e = 0.0271$), being larger in the MACH condition. Similar results were obtained from the SSTM-ODD/MACH-ODD analysis. This factor also tends to be larger for the rare than for the frequent stimuli in the

MACH-ODD condition ($F(1/7) = 9.74$, $MS_e = 0.005$). These analyses thus corroborate the inferences we drew from the grand averages concerning the $\overline{N140}$ component.

The component which peaks 200 msec after the stimulus is related to the $\overline{P200}$ component of the ERP. It is largest at C_z with a sharp frontal gradient ($F(8/56) = 4.04$, $MS_e = 0.0015$ for SSTM/MACH). None of its relations to other experimental variables are statistically significant.

It seems reasonable to identify the prestimulus component with the Readiness Potential (RP). In both data-sets there is an interaction between the mode of stimulus presentation and the recording electrode ($F(8/56) = 3.19$, $MS_e = 0.0007$ for SSTM-ODD/MACH-ODD). An examination of the factor-scores shows this component to be present primarily at the central electrodes in the self-stimulation conditions. Moreover, it is larger at C_3 than at C_4 , as would be expected of an RP with the subjects responding with their right hand (Kutas & Donchin, 1974).

The component associated with the later part of the epoch displays complex relationships with the independent variables. For the SSTM/MACH analysis, this component appears positive-going at all electrode sites. It is maximal at C_z for the SSTM waveforms while essentially absent for the MACH condition ($F(1/7) = 5.33$, $MS_e = 0.0117$). The SSTM-ODD/MACH-ODD analysis shows that both mode of stimulus presentation and probability of presentation affect the distribution of this factor. The three-way interaction of these variables ($F(8/56) = 2.39$, $MS_e = 0.0006$) summarizes these complex effects (see Figure 5). For the computer-presented rare tones, this component is negative going in the frontal electrodes, is nearly absent in the centrals, and is positive going in the parietal electrode. For the computer-generated frequent tones, this component is near zero for all

Fig. 5

electrode positions. Thus, this component has many of the attributes of the Slow Wave (SW) component of the ERP originally described by Squires, N. et al. (1975). For the self-triggered frequent tones, this factor is positive at all sites, while for the rares it is much reduced or zero at each site. This result may reflect a complex interaction between two slow positive components, one relating to the rarity of the stimulus while the other is related to the motor response.

The component peaking at 380 msec is unique to the SSTM-ODD/MACH-ODD data. The factor-scores indicate that this factor is largest parietally ($F(8/56) = 9.46$, $MS_e = 0.0007$) and appears only to the rare tones ($F(1/7) = 14.79$, $MS_e = 0.0146$). This component can thus be identified as the $\overline{P300}$ component. Note that mode of stimulus presentation strongly affects this factor. At C_z , $\overline{P300}$ is larger for self-stimulation than for machine-presented stimuli ($F(8/56) = 2.12$, $MS_e = 0.0004$). This effect is much reduced at P_z .

To summarize, five distinct components emerge from the combined data and show systematic relationships with the experimental variables. The $\overline{NT40}$, $\overline{P200}$, RP, and SW components appear in both data sets. There is reason, however, to suspect different bases for the SW component in each data set; a frontal-negative, parietal positive-going wave to machine presented rare tones as described by N. Squires et al. (1975), and a central dominant positive-going wave related to movement. The $\overline{P300}$ component is uniquely associated with the rare tones presented in the oddball paradigms. We have not found $\overline{P300}$ to be associated with all stimuli whose time of occurrence is uncertain. Yet, the mode of stimulus presentation does affect the distribution of $\overline{P300}$, seeming to reduce its amplitude at C_z , without much of an effect on its amplitude at P_z .

DISCUSSION

To a degree, our data confirm the report by Schafer and Marcus (1973). The ERPs associated with stimuli which have been triggered by the subject are indeed different from ERPs elicited by the same stimuli when triggered by a computer. Yet in detail our data paint a picture quite different from that outlined by Schafer and Marcus, who reported effects which seemed equally potent for all components of the ERP. A global enhancement of the ERP waveform is often attributed to generalized changes in the subject's arousal level (Haider, Spong, & Lindsley, 1964). A strong case can, however, be developed against attempts to treat the ERP as a global unitary phenomenon whose components respond in unison to experimental manipulations (Donchin, 1969, 1975). The weight of the evidence leans towards a view of the ERP as a sequence of serially elicited components, representing distinct intra-cerebral processes, each responding in a distinct way to experimental manipulations (Picton, Hillyard, Krausz, & Galambos, 1974).

The data reported here are in accord with the view of the ERP as a sequence of components. Again, the effects of different experimental variables were localized to a subset of the ERP components. As has been repeatedly shown in the past, the presentation of task relevant, rare, events, is associated with a large P300 component (cf. Price & Smith, 1974 for bibliography). Two effects are associated with the mode of stimulus triggering, a Readiness Potential precedes the switch closure in the SSTM conditions and the N140 component of the ERP is enhanced when the stimulus is presented at a temporal sequence which the subject cannot reliably predict (in the NACH conditions).

At first inspection, the N140 component elicited by subject-triggered tones appears earlier in latency than that elicited by computer-triggered tones,

as reported by Schafer and Marcus (1973). However, after correction for movement-related potentials, this latency shift can no longer be observed. The failure of Schafer and Marcus to see such movement-related potentials in their data may be due to the frequency response of their recording system. They report their amplifiers to have a low cutoff point at 3 Hz, clearly above the range required for recording Readiness Potentials.

Subtraction of the estimated contribution of the Readiness Potentials affected the observed amplitude of $NT40$. In the SSTM condition there seemed to be virtually no ERP waveform after the RPs were subtracted. In the SSTM-ODD and in the MACH-ODD, a clear auditory ERP could be observed in the residuals. Moreover, the $NT40$ was larger in the MACH-ODD than in the SSTM-ODD, especially in association with the rare tones. It is possible, then, that these data present yet another demonstration of the lability of the $NT40$ component and its sensitivity to the direction of the subject's attention to stimuli. Hillyard and his associates (Hillyard, Hink, Schwent, & Picton, 1973; Picton & Hillyard, 1974) have reported that the amplitude of "N1", which we assume to be identical to our $NT40$, is enhanced when subjects direct their attention to one of several, simultaneously presented, sources of information. It is plausible to assume that on a scale of task-demands, the SSTM condition ranks lowest. The SSTM-ODD, in which the subject has to discriminate the intensity of a stimulus whose arrival time he knows ranks second, while the MACH-ODD condition in which stimulus arrival time is also unknown is most demanding. This, of course, is a post-hoc explanation of the "self-stimulation" effect as we have no independent measure of the subject's attentional strategies. Yet it is consistent with the data. Localizing the effect to a specific component whose response to experimental variables is known enables an interpretation of the effect within a valid framework.

The effects of temporal uncertainty on the $P300$ component are of interest. We find that by itself, temporal uncertainty is not sufficient to elicit a $P300$. This component appeared only in response to rare stimuli, and at the parietal electrodes it seemed not to matter whether the stimulus was machine or subject-generated.

One cannot deduce from these data that temporal uncertainty never affects $P300$ amplitude. It is conceivable that the degree of uncertainty associated with the temporal characteristics of the stimulus train was lower than that associated with the occurrence of the rare and frequent stimuli. A definitive answer awaits the development of commensurate scales of temporal and event uncertainty. Yet it is interesting that while temporal uncertainty did affect the $N140$ component it failed to enhance $P300$. Such a dissociation between $N140$ and $P300$ effects is consistent with the findings of Ford, Roth, Dirks, and Kopell (1973). It implies, we believe, that unlike $N140$ which may be related to generalized allocation of attention to a task, or to an information source, $P300$ is a manifestation of the activation of a specific processor called into action by the information conveyed by the specific stimuli in the sequence. The present data suggest that the serial context within which the stimuli are presented is more important than fluctuations in stimulus presentation time. Again we find as did Donchin, Kubovy, Kutas, Johnson, and Herning (1973) that "uncertainty reduction" by itself does not suffice as an explanatory concept for the $P300$ component.

In this, our conclusions differ from those drawn by Ford et al. (1976). These investigators presented subjects with tones designated as targets at a rate of 1 per second. These were to be compared to standard tones presented at the rate of 1, 2 or 4 per second. The varying rate of standard presentation

resulted in different sequential probabilities for the appearance of the target. Ford et al. did not find sequential probability to have an effect on P_{300} amplitude. They attribute, therefore, the P_{300} differences they did observe to temporal uncertainty. Yet, we note that they confound sequential with global probability. As they increase the rate of standard presentation, the number of standard stimuli per unit time increases. As they were unable to dissociate the multiple effects of stimulus density, it is difficult to accept their data as demonstrating an effect of temporal uncertainty on P_{300} .

Strangely, temporal uncertainty appears to selectively diminish the amplitude of the P_{300} component at the central electrodes. The diminution of P_{300} at C_z in the MACH-ODD condition cannot be attributed to an increase in the temporal jitter in the response to stimuli whose time of arrival is unknown. Such temporal jitter would have affected P_z and C_z to an equal extent. Note that the shape of the P_{300} at P_z is equally peaked for both the SST4-ODD and MACH-ODD conditions. The dissociation between parietal and central P_{300} cannot be attributed to positive components of the RP as the difference survives subtraction of the RP (see Figure 3).

This dissociation between the P_z and the C_z P_{300} has not been previously reported, and unfortunately, a ready explanation cannot be derived from these data. Perhaps the long interstimulus intervals are a factor. In fact the correlation between ISI and P_{300} (measured by the factor scores) is $-.587$ indicating that P_{300} tends to be diminished with increasing ISI. Further research is clearly required on the relationships between P_{300} amplitudes and the temporal sequence of the stimulus series. As Donchin and Smith (1970) have stated, "These results point to the importance of considering the experimental situation in an AEP experiment not as a series of isolated stimuli, the response

to which is to be determined, but as a continuous, on-going process in which the subject's response to each stimulus is conditioned by his expectancies with regard to future stimuli and his experiences with past stimuli." The details of the stimulus presentation sequences, as well as the successive intervals between stimuli appear to be equally important. Studies in this laboratory, reported elsewhere (Squires, Wickens, Squires, & Donchin, submitted) demonstrate a strong relationship between P_{300} amplitude and the disconfirmation of expectancies, where expectancy is determined by multiple factors such as the global probability of a stimulus, the immediate past history of stimulus presentations as well as the microstructure of the series. Thus, the effects of either temporal or event uncertainties must be assessed in terms of trial-by-trial variations in expectancy, rather than as consequences of loosely defined uncertainties.

In conclusion Schafer and Marcus were correct in pointing out the importance of stimulus presentation mode on the waveform of the ERP. The effects, however, appear to be distinct at different ERP components and may well be a corollary of the effects which presentation mode may have on the subject's perception of his tasks.

REFERENCES

- Davis, H., Mast, T., Yoshie, N., & Zerlin, S. The slow response of the human cortex to auditory stimuli: Recovery process. Electroencephalography and Clinical Neurophysiology, 1966, 21, 105-113.
- Dickman, K. W. SOUPAC Program Descriptions. DCL Report No. UIUCDCS-R-72-370-4, University of Illinois, Urbana-Champaign, 1974.
- Donchin, E. A multivariate approach to the analysis of average evoked potentials. IEEE Transactions of Bio-Medical Engineering, 1966, 13, 131-139.
- Donchin, E. Average evoked potentials and uncertainty resolution. Psychonomic Science, 1968, 12, 103.
- Donchin, E. Data analysis techniques in evoked potential research. In E. Donchin and D. B. Lindsley (Eds.) Average Evoked Potentials; Methods, Results, and Evaluations. NASA, Government Publications Office, Washington, D.C., 1969, SP-191, 199-236.
- Donchin, E. Brain electrical correlations of pattern recognition. In G. F. Inbar (Ed.), Signal Analysis and Pattern Recognition in Biomedical Engineering. New York: John Wiley & Sons, 1975.
- Donchin, E., & Cohen, L. Averaged evoked potentials and intramodality selective attention. Electroencephalography and Clinical Neurophysiology, 1967, 22, 537-546.
- Donchin, E., & Heffley, E. Minicomputers in the signal-averaging laboratory. American Psychologist, 1975, 30, 299-312.
- Donchin, E., Kubovy, M., Kutas, M., Johnson, R., Jr., & Herning, R. I. Graded changes in evoked response (P300) amplitude as a function of cognitive activity. Perception & Psychophysics, 1973, 14, 319-324.

- Donchin, E., & Smith, D. B. D. The contingent negative variation and the late positive wave of the average evoked potential. Electroencephalography and Clinical Neurophysiology, 1970, 29, 201-203.
- Donchin, E., Tueting, P., Ritter, W., Kutas, M., & Heffley, E. On the independence of the CNV and the P300 components of the human averaged evoked potential. Electroencephalography and Clinical Neurophysiology, 1975, 38, 449-461.
- Ford, J. M., Roth, W. T., Dirks, S. J., & Kopell, B. S. Evoked potential correlations of signal recognition between and within modalities. Science, 1973, 181, 465-466.
- Ford, J. M., Roth, W. T., & Kopell, B. S. Auditory evoked potentials to unpredictable shifts in pitch. Psychophysiology, 1976, 13, 32-39.
- Haider, M., Spong, P., & Lindsley, D. B. Attention, vigilance and cortical evoked-potentials in humans. Science, 1964, 145, 180-182.
- Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. Electrical signs of selective attention in the human brain. Science, 1973, 182, 177-180.
- Kutas, M., & Donchin, E. Studies of squeezing: Handedness, responding hand, response force, and asymmetry of readiness potential. Science, 1974, 186, 545-548.
- Lehtonen, J. B. Functional differentiation between late components of visual evoked potentials recorded at occiput and vertex: Effect of stimulus interval and contour. Electroencephalography and Clinical Neurophysiology, 1973, 35, 75-82.

- Picton, T. W., & Hillyard, S. A. Human auditory evoked potentials. II: Effects of attention. Electroencephalography and Clinical Neurophysiology, 1974, 36, 191-199.
- Picton, T. W., Hillyard, S. A., Krausz, H. I., & Galambos, R. Human auditory evoked potentials. I. Evaluation of components. Electroencephalography and Clinical Neurophysiology, 1974, 36, 179-190.
- Price, R. L., & Smith, D. B. D. The P(300) wave of the averaged evoked potential: A bibliography. Physiological Psychology, 1974, 2, 387-391.
- Ritter, W., Vaughan, H. G., & Costa, L. D. Orienting and habituation to auditory stimuli: A study of short term changes in averaged evoked responses. Electroencephalography and Clinical Neurophysiology, 1968, 25, 550-556.
- Rothman, H. H., David, H., & Hay, I. S. Slow evoked cortical potentials and temporal features of stimulation. Electroencephalography and Clinical Neurophysiology, 1970, 29, 225-232.
- Schafer, E. W. P., & Marcus, M. M. Self-stimulation alters human sensory brain responses. Science, 1973, 181, 175-177.
- Squires, K. C., Donchin, E., Herning, R. I., & McCarthy, G. On the influence of task relevance and stimulus probability on ERP components. Electroencephalography and Clinical Neurophysiology, in press.
- Squires, K. C., Wickens, C., Squires, N. K., & Donchin, E. The effect of stimulus sequence on the waveform of the cortical event-related potential. Submitted for publication.

- Squires, N. K., Squires, K. C., & Hillyard, S. A. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. Electroencephalography and Clinical Neurophysiology, 1975, 38, 387-401.
- Sutton, S., Braren, N., Zubin, J., & John, E. R. Evoked-potential correlates of stimulus uncertainty. Science, 1965, 155, 1436-1439.

FOOTNOTE

¹All references to statistical significance assume an alpha level of .05 ($p < .05$).

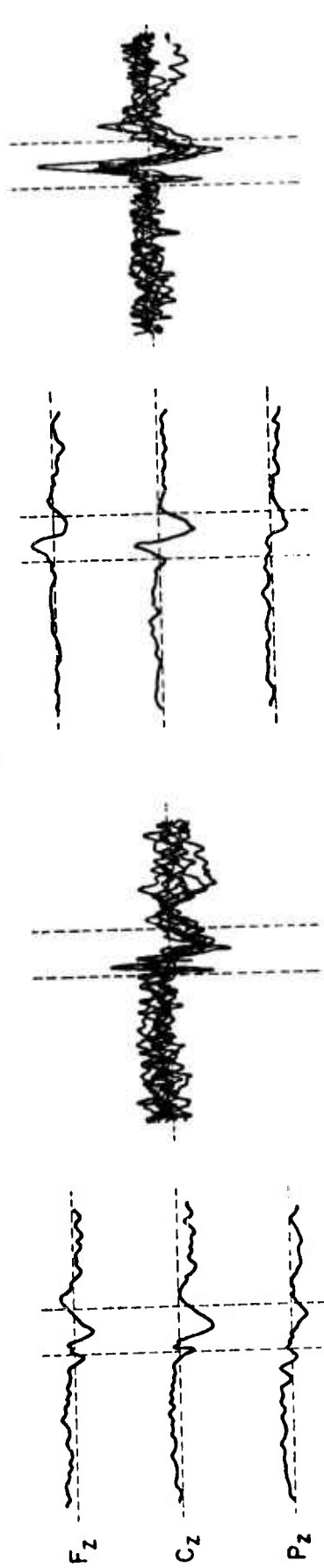
FIGURE LEGENDS

- Figure 1. Waveforms of the ERP, obtained by averaging data from all subjects, are depicted for each experimental condition. Averages for each of the eight subjects are overlapped for the SSTM, MACH, and CONT conditions to illustrate the degree of intersubject variability. Upward deflections, in all waveforms, represent negative polarity.
- Figure 2. Averaged waveforms for subject D.H. for each of the experimental conditions are shown. Waveforms elicited by subject and machine presented tones are overlapped for the SSTM/MACH and SSTM-ODD/MACH-ODD (both frequent and rare tones) conditions.
- Figure 3. Grand-averaged waveforms elicited by subject and machine initiated tones are shown overlapped. The lower traces for the subject initiated conditions represent those data after point by point subtraction of the motor control (CONT) waveforms. In both upper and lower traces, the machine initiated conditions are the same to allow comparison.
- Figure 4. Factor loadings for both SSTM/MACH and SSTM-ODD/MACH-ODD analyses are plotted. The numbering of each component is with reference to their discussion in the text and not in the order of their extraction by the Varimax rotation procedure. The analyses were performed on 2000 msec of data, including 1000 msec of prestimulus EEG.
- Figure 5. The mean factor scores for the electrode X mode (of stimulus presentation) X stimulus probability interaction for the long latency slow component (IV from Figure 4) of the SSTM-ODD/MACH-ODD analysis are depicted.

SSTM

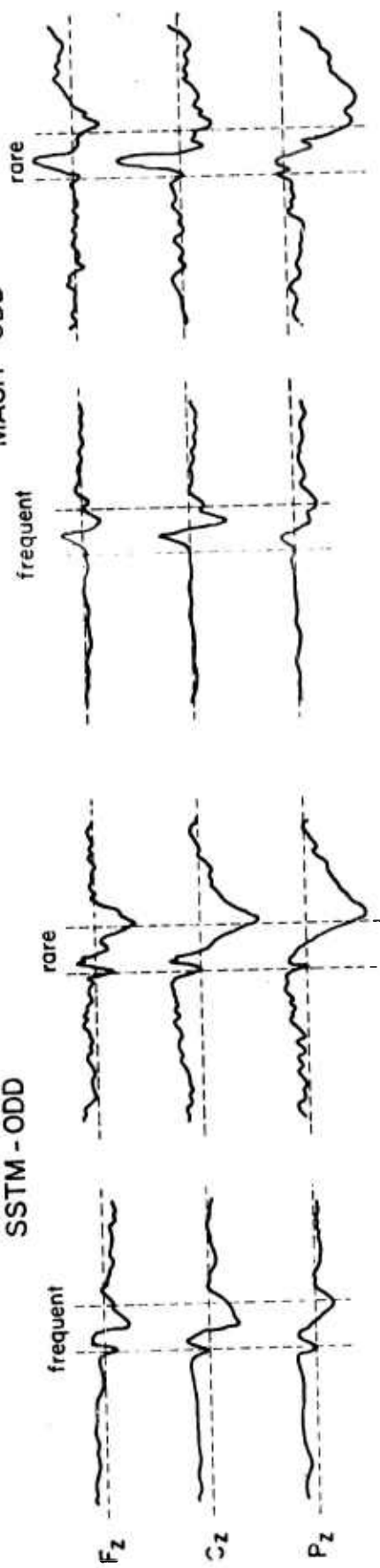
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MACH



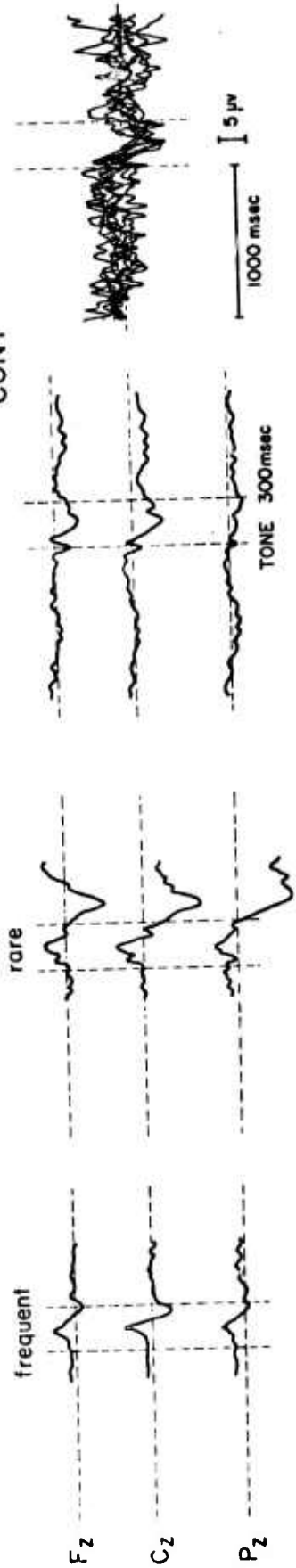
SSTM - ODD

MACH - ODD



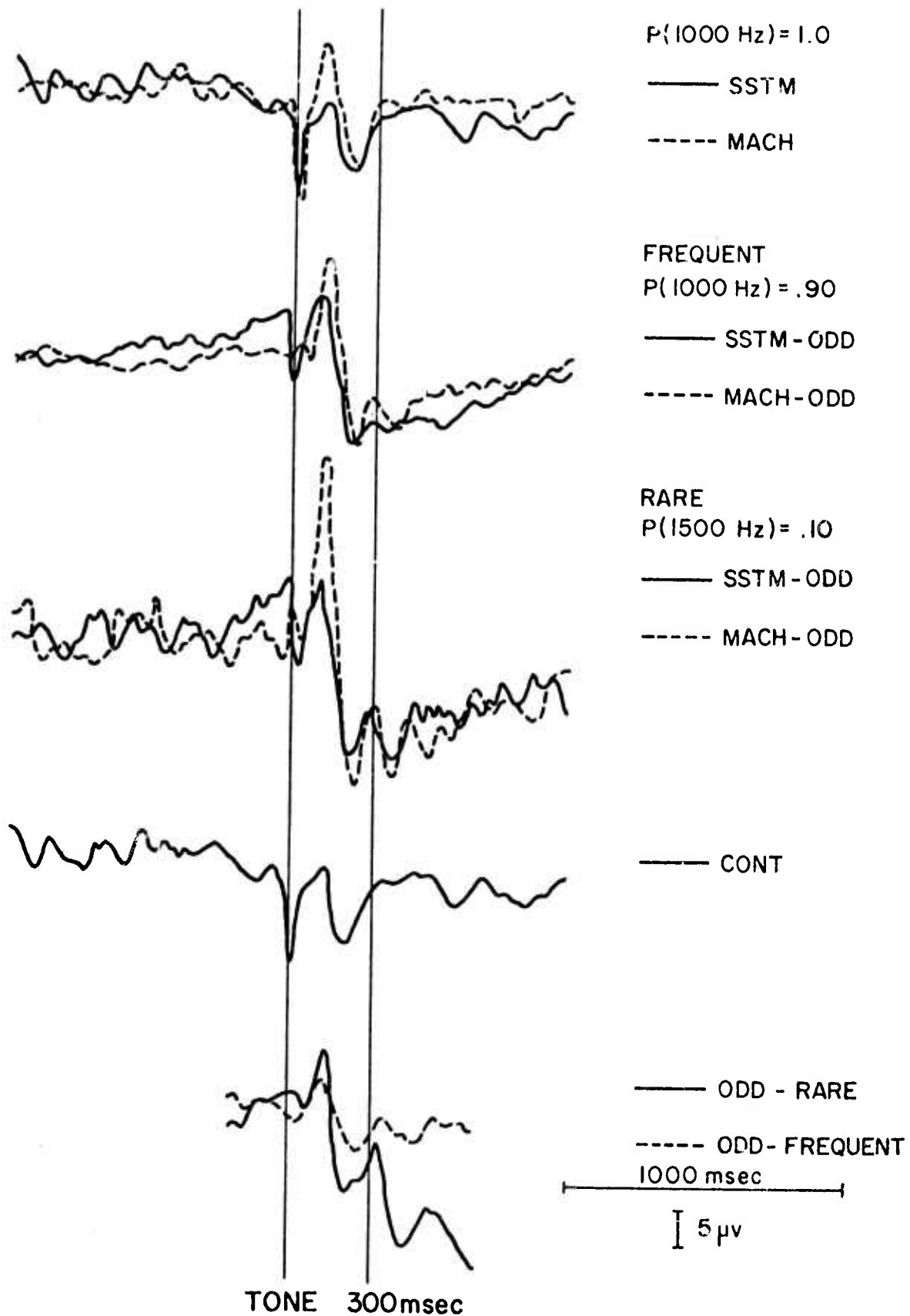
ODD

CONT



134<

SUBJECT D. H.

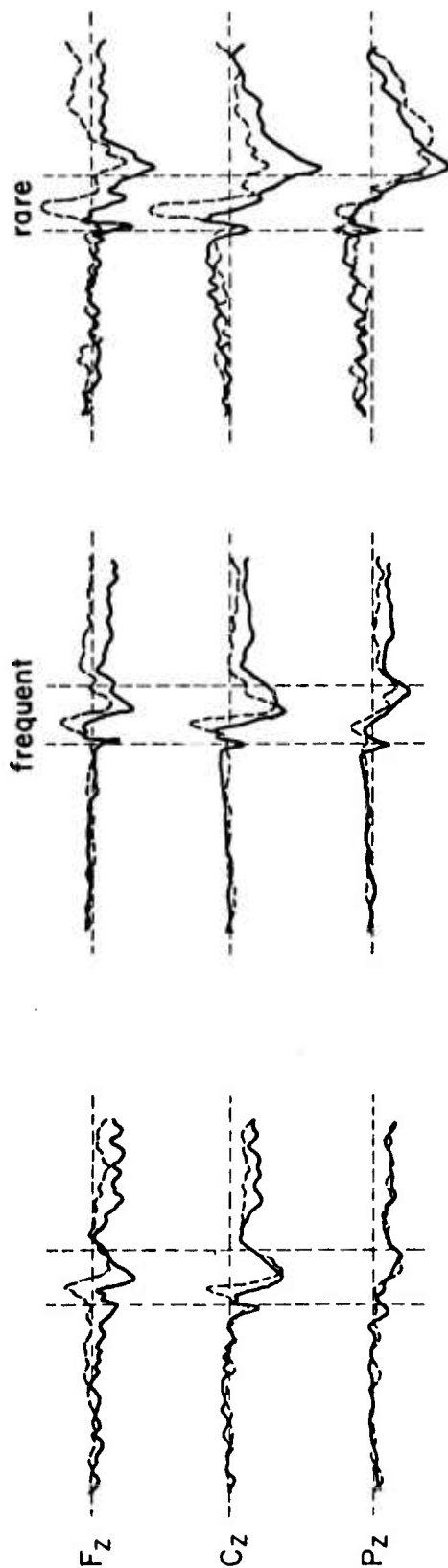


BEFORE SUBTRACTION

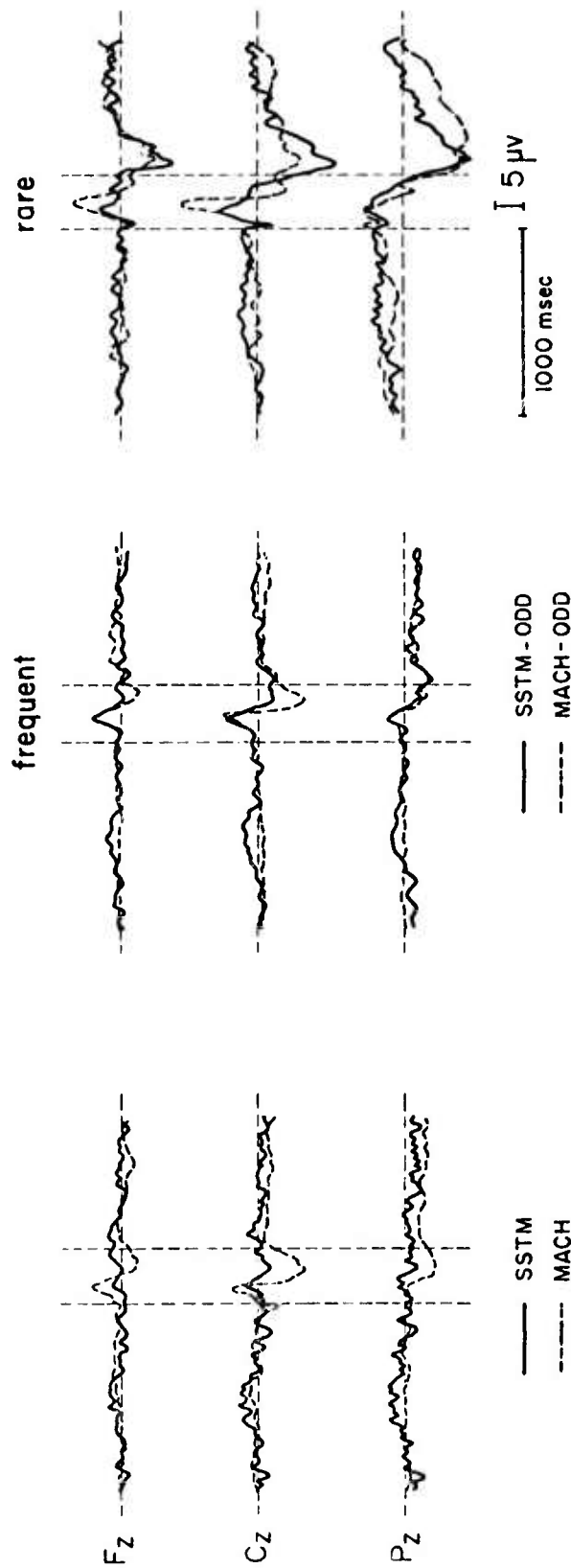
105<

SSTM / MACH

SSTM - ODD / MACH - ODD

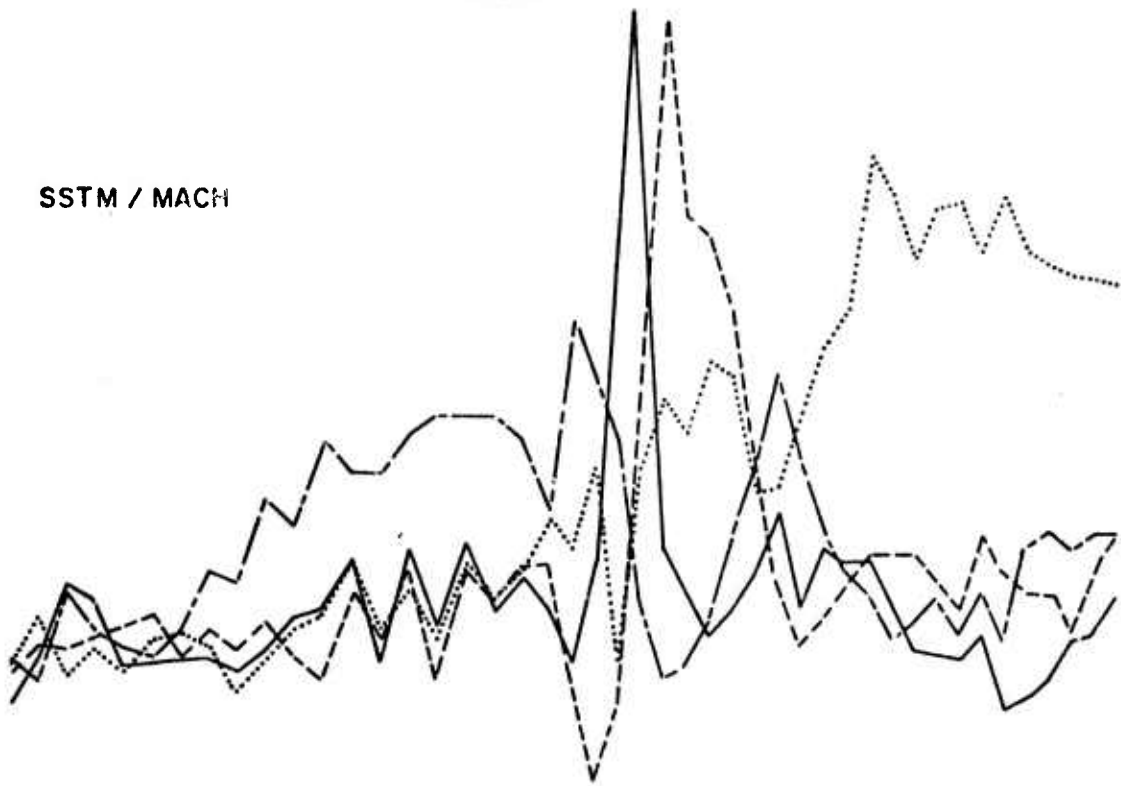


AFTER SUBTRACTION



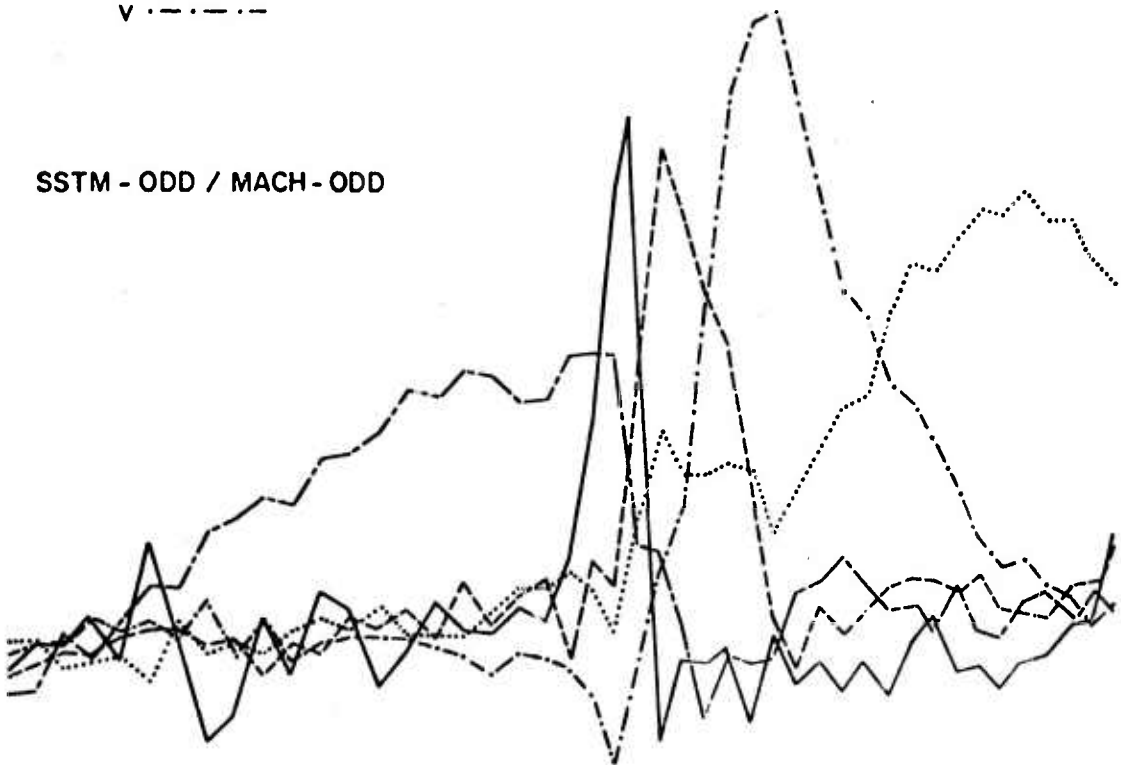
136<

SSTM / MACH

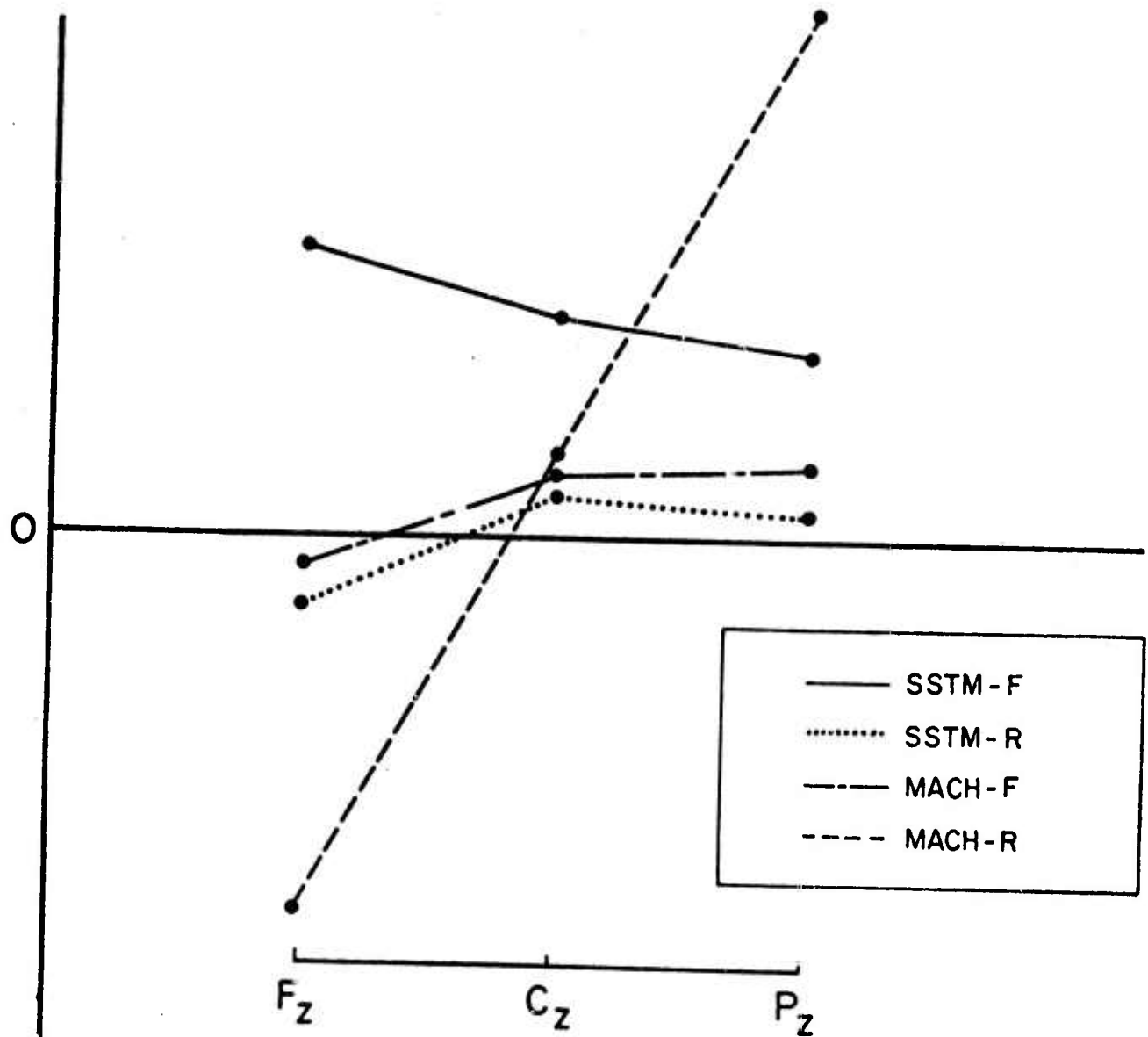


I ———
II ———
III ———
IV
V - . - . -

SSTM - ODD / MACH - ODD



1000 msec.



VARIATIONS IN THE LATENCY OF $\overline{P300}$ AS A FUNCTION OF
VARIATIONS IN SEMANTIC CATEGORIZATIONS

M. Kutas and E. Donchin
Department of Psychology
University of Illinois
Champaign, Illinois 61820

Several recent studies of $\overline{P300}$ utilized the following experimental paradigm. The subject is presented with a stream of stimuli, each of which may belong to one of two categories. The subject counts and reports verbally the number of stimuli which belong to one of the two categories. The probability is low that a stimulus will belong to one of the categories and correspondingly high that it will belong to the other category. Stimuli categorized into the low probability category elicit an enhanced $\overline{P300}$ component (Ritter & Vaughan, 1969; Squires, Squires & Hillyard, 1975; Tueting, Sutton & Zubin, 1971). In most of the experiments reported to date, the categorizations required of the subject were based on such physical features of the stimuli as the frequency of tones, the hue of light flashes, the specific pattern of the visual stimulus etc. It seemed necessary to determine if the same results would be observed if the categorization required of the subject was based on semantic features of the stimuli (see Friedman, Simson, Ritter & Rapin, 1975). For this purpose we presented 6 subjects with sequences of words. Each word could be categorized on the basis of a semantic rule, into one of two categories. The two categories appeared with the probability of either .20 or .80. Our intent was to determine the extent to which the appearance of stimuli belonging to the rare category would enhance the $\overline{P300}$ component. As the complexity and latency of the categorization response depended on the complexity of the categorization, the data could also be examined for the relationship between the duration of the cognitive operations required of the subject and the latency of the $\overline{P600}$

component. If $P300$ is a manifestation the invocation of a specific cognitive processing activity (Donchin, 1975; Donchin, Kubovy, Kutas, Johnson & Herning, 1973) then the latency of the $P300$ relative to the physical stimulus would depend on the latency and duration of the cognitive process and would vary as a function of the complexity, and therefore the duration, of the cognitive process. This proposition was tested in the present study.

The experiment utilized PLATO, a computer assisted instruction system developed at the University of Illinois. The PLATO terminal uses a plasma panel for display (Stifle, 1974). Several hundred such terminals are supported by a central computer facility. The terminal provides for the presentation of rather elaborate graphics and an almost unlimited range of possibilities for presenting visual stimuli to the subject. The terminal is also provided with an external trigger output which can be generated under program control. The display is achieved by illuminating any of 512 x 512 luminous dots. In this experiment the PLATO system was programmed to present a sequence of words on the terminal, one at a time. Each word was preceded by an external trigger signal which was led to a PDP8/e computer. This trigger activated the digitizing process so that EEG data would be acquired in relation to the presentation of the stimuli.

We report here data from three studies. In each study subjects were presented with four different sequences of words. Each sequence consisted about 250 words, each belonging to one of two categories. Each stimulus was selected randomly on any trial with the appropriate probability. The series used are described below.

(1) Fixed names. The words presented to the subjects would be either "Nancy" or "David." The name "Nancy" appeared 20% of the time.

(2) Variable names. The words presented to the subject could be selected from a list of 20 female names and 20 male names. 20% of the names selected were from the female name list and 80% from the male name list (e.g., Larry).

Henry).

(3) Rhymes. The words were selected either from a list of words rhyming with the word "cake" (e.g., steak, bake) or from a list of 20 arbitrary words. The rhymes were presented 20% of the time.

(4) Synonyms. The words selected were from a list of 20 arbitrarily chosen words and 9 synonyms of the word "prod" (e.g., poka, goad). The synonyms were presented 20% of the time.

Brain potentials were monitored with Burden electrodes placed at Fz, Cz, Pz, C3 and C4 referred to linked mastoids in the first experiment and the chin in the others. The EOG was recorded between supraorbital and canthal positions. The subject was grounded on the forehead. The EEG was amplified by Brush amplifiers (#11-4307-02) with a 2 sec time constant and 30 Hz high frequency cut-off (1/2 amplitude). A Hewlett Packard FM tape recorder (3955) was used to record analog data. Recording was done at 1 7/8 inches per second. Data were digitized off-line by an IBM 1800 and stored on digital magnetic tape. Digitizing started 250 msec prior to the stimulus and ended 1000 msec later. The sampling rate was 10 msec per point. A PDP 8/e computer determined, on line, whether eye movement artifacts were present during each trial by comparing the EOG variance to a criterion value. Contaminated trials were not included in the average.

The subject sat in a comfortable chair in a semi-darkened shielded room. Each subject was run through the different conditions in order: Fixed names, Variable names, Rhymes and Synonyms. Prior to each block of approximately 250 trials the subject was instructed to watch the words and count stimuli from the rare category. At the end of each session, the subject was asked to report his count.

Six subjects were run in the first experiment in which the subject's task was to count the number of stimuli belonging to the rare category. Figure 1

Insert Figure 1 Here

presents the data from one subject and super-averages computed over the data from the entire subject group. Evoked responses elicited by stimuli belonging to the frequent category lack a $\overline{P300}$ component. The ERPs elicited by stimuli belonging to the rare category show a marked $\overline{P300}$ component. Also, the latency of the $\overline{P300}$ component varies widely. The latency is shortest for the fixed-name categorization and longest for the synonyms. The variable names and the rhyming words show intermediate latencies. This ranking of latencies characterize the data obtained from all subjects. There were also differences in the amplitude of the $\overline{P300}$ component over the four conditions.

These data demonstrate that the $\overline{P300}$ response is associated with the categorization of the stimuli even when the categorization depends on semantic rather than on physical characteristics of the stimuli. Even though averaging is over a diverse array of physical stimuli, such as the different female names used in these lists, a clear $\overline{P300}$ response is elicited. The data are consistent with the suggestion that the latency of $\overline{P300}$ varies systematically with the complexity of information processing required of the subject, suggesting that $\overline{P300}$ latencies, even though varying with respect to the physical stimulus, are uniform relative to the time at which the putative cognitive activity underlying their appearance occurs. This conclusion is supported by the fact that there were no apparent differences in the scalp distribution of the $\overline{P300}$ associated with the four series.

In an attempt to validate the extent to which the differences between the series are in fact related to different subject decision-times, we repeated the experiment with 5 other subjects, asking that they respond rapidly by pressing one of two buttons upon the appearance of any stimulus from the two categories. The results are shown in Figure 2. The data obtained in Experiment

Insert Figure 2 Here

2 differ from those obtained in Experiment 1 in two important respects. First, it appears that the execution of a motor response changes the appearance of the "frequent" evoked response in that a positive component, presumably the P2 of the motor potential, can be observed. This positivity cannot fully account for the rather marked enhancement of the positivity with the latency of about P400 associated with the rare stimuli. The latencies obtained in this second experiment, however, are somewhat less differentiated than those observed in the first experiment. The fixed names latency is still considerably shorter than that associated with the other three conditions, however, these three conditions are no longer as differentiated as they were during the count condition. The reaction times associated with these four experimental conditions are consistent with the latencies of P300.

The failure to observe differences in the latency of P300 with 3 of the 4 experimental conditions could be attributed to the fact that in the second experiment we emphasized speed without requiring the subject to be accurate in his categorizations. Thus subjects tended to execute erroneous categorizations as they attempted to minimize their response speed. The error rate across the different experimental conditions varied. Clearly, subjects could have traded accuracy for speed. A third experiment was therefore run. This time we did not use the "rhymes" series. Each subject was run under three experimental conditions, with each of the series. The "count" condition replicated Experiment 1; the "RT-Speed" condition replicated Experiment 2 while in the "RT-Accurate" condition subjects made a choice reaction to the stimulus but were instructed to be very accurate, never pressing the wrong button. The results are shown in Figure 3. Clearly, when accuracy is emphasized P300

 Insert Figure 3 Here

latencies vary with the series in the same manner they vary in the "count" conditions. When speed is of prime consideration, the subjects seem to maximize speed by reducing the processing time they invest in the categorization, thereby reducing the variability in $\overline{P300}$ latency.

We conclude, then, that the latency of the late positive component which is associated with rare occurrences of relevant stimuli varies with cognitive processing time. These data are consistent with the view that the variable latency, parietal maximum, late positive waves are manifestations of the activity of the same intracranial processor.

References

- Donchin, E. Brain electrical correlates of pattern recognition. In G. F. Inbar (Ed.) Signal Analysis and Pattern Recognition in Biomedical Engineering. New York: John Wiley, 1975. Pp. 199-218.
- Donchin, E., Kubovy, M., Kutas, M., Johnson, R., & Herning, R. I. Graded changes in evoked response (P300) amplitude as a function of cognitive activity. Perception and Psychophysics, 1973, 14: 319-324.
- Friedman, D., Simson, R., Ritter, W., & Rapin, I. The late positive component (P-300) and information processing in sentences. Electroencephalography and Clinical Neurophysiology, 1975, 38: 255-262.
- Ritter, W., & Vaughan, J. H. Average evoked responses in vigilance and discrimination: A reassessment. Science, 1969, 164: 326-328.
- Squires, N., Squires, K., & Hillyard, S. A. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. Electroencephalography and Clinical Neurophysiology, 1975, 38: 387-401.

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Stifle, J. The Plato IV Student Terminal, CERL Report X-15, University of Illinois, Urbana, Illinois, 1974.

Tueting, P., Sutton, S., & Zubin, J. Quantitative evoked potential correlates of probability of events. Psychophysiology, 1971, 7: 385-394.

Figure Legends

- Figure 1. Superimpositions of the average ERPs obtained during the four different experimental conditions requiring different semantic categorizations. At the top are sample Cz waveforms to the rare and frequent stimuli from an individual subject. The remaining waveforms are superaverages across all six subjects for the Fz, Cz and Pz positions, respectively. Only the rare stimuli (prob. = .20) were counted. Each rare waveform consists of approximately 20-30 single trials.
- Figure 2. Superimposition of ERPs averaged across 5 subjects from the 4 different experimental conditions for the frontal, central and parietal electrode positions. Subjects were required to perform a choice reaction time response, responding to frequent stimuli with one hand and rare stimuli with the other.
- Figure 3. Superimposition of the vertex ERPs averaged across subjects for 3 different semantic categorizations obtained during 3 different response requirement regimes. During the collection of the top waveforms subjects were asked to keep a running count of the rare stimuli. The middle waveforms represent responses to rare and frequent stimuli to which subjects made choice RT responses under orders to be as accurate as possible. The bottom waveforms were obtained under similar choice RT response requirements with the emphasis on speed rather than accuracy.

FREQUENTS

RARES

RG

SUPER AVERAGES

FRONTALS

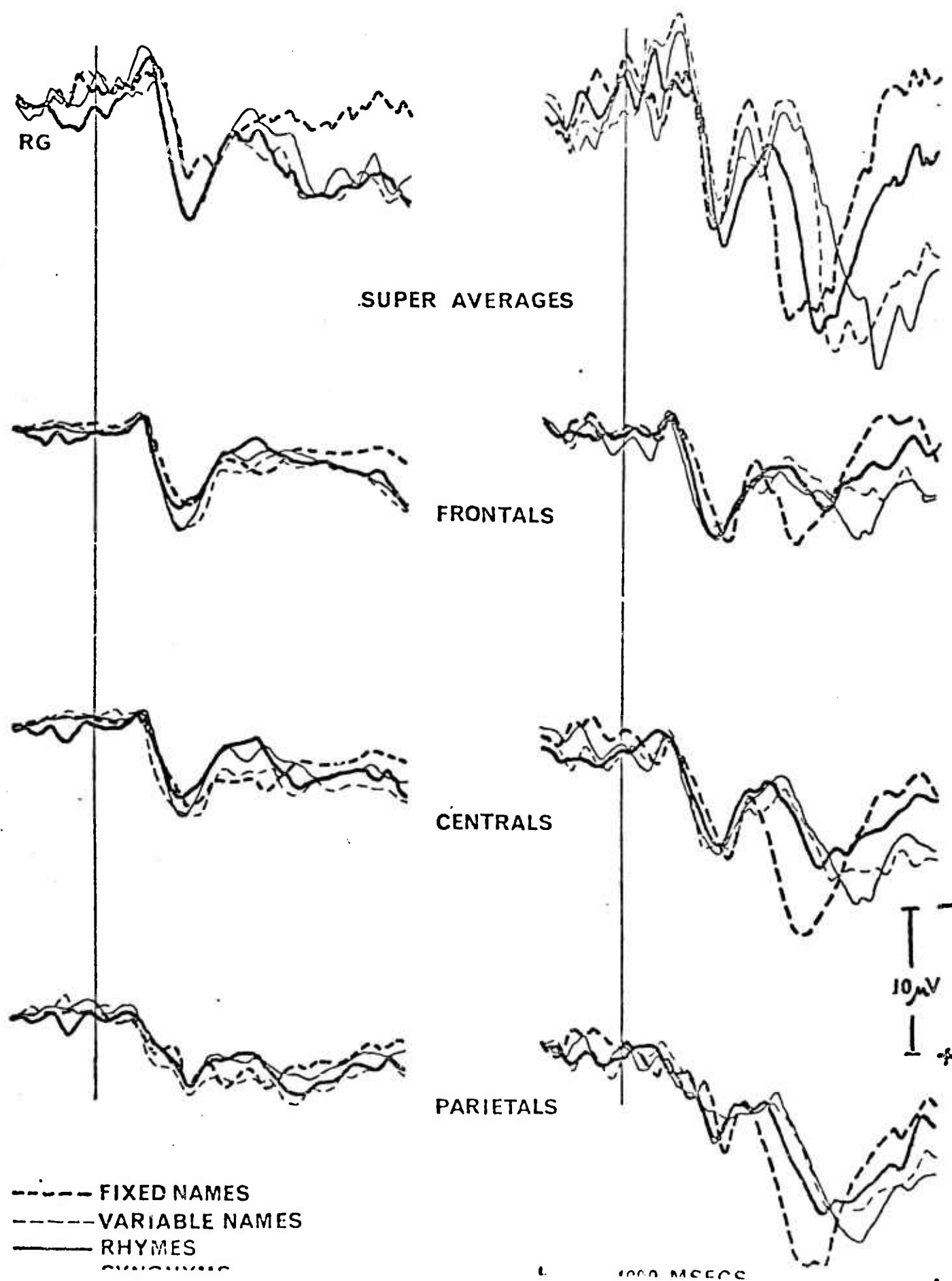
CENTRALS

PARIETALS

10 μ V

----- FIXED NAMES
 ----- VARIABLE NAMES
 ——— RHYMES

1000 MSEC



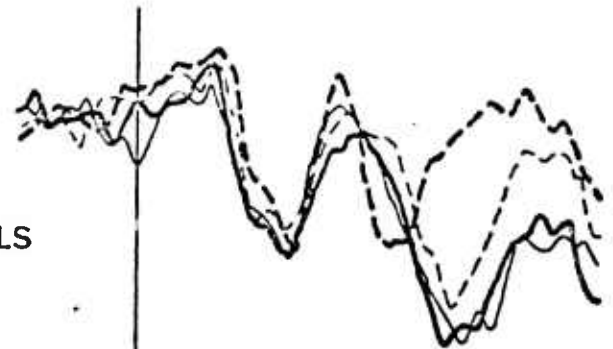
SUPER AVERAGES

FREQUENTS

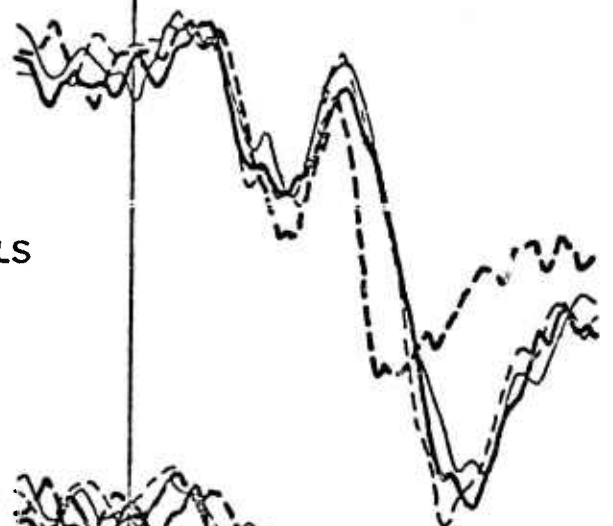
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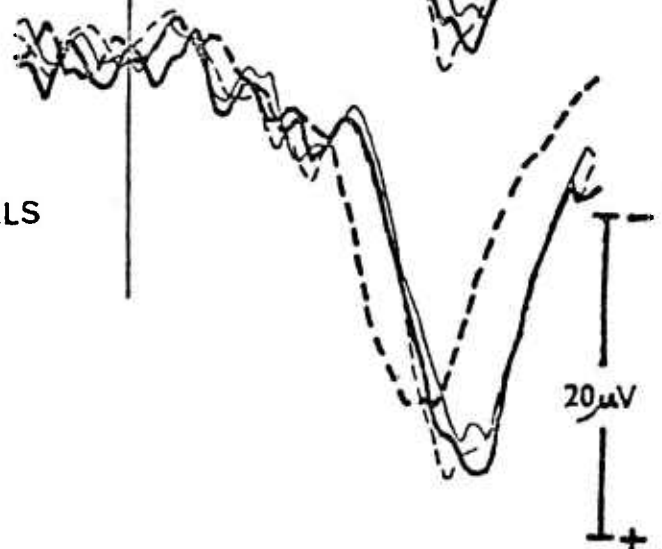
FRONTALS



CENTRALS



PARIETALS



----- FIXED NAMES
----- VARIABLE NAMES
----- RHYMES
----- SYNONYMS

1000 MSECS

SUPER AVERAGES

FREQUENTS

148<

RARES

COUNT

ACCURATE
CHOICE RT

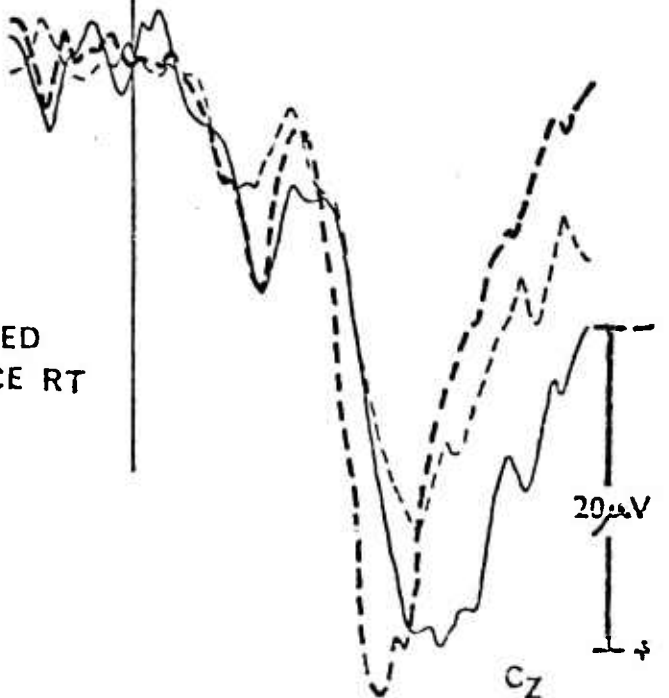
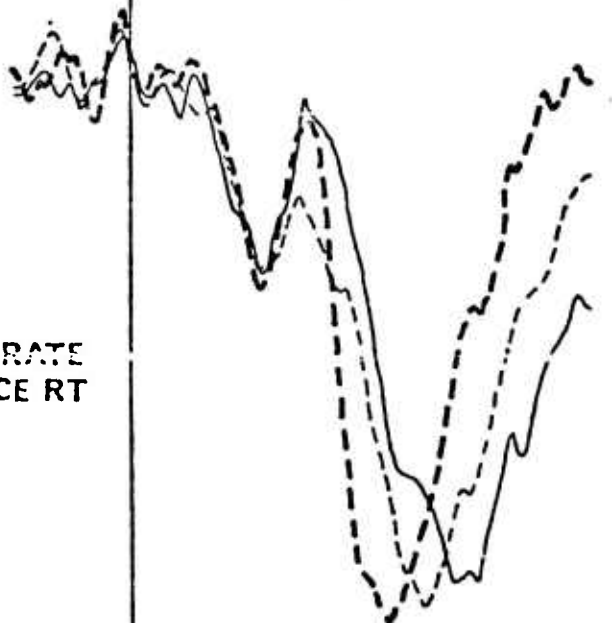
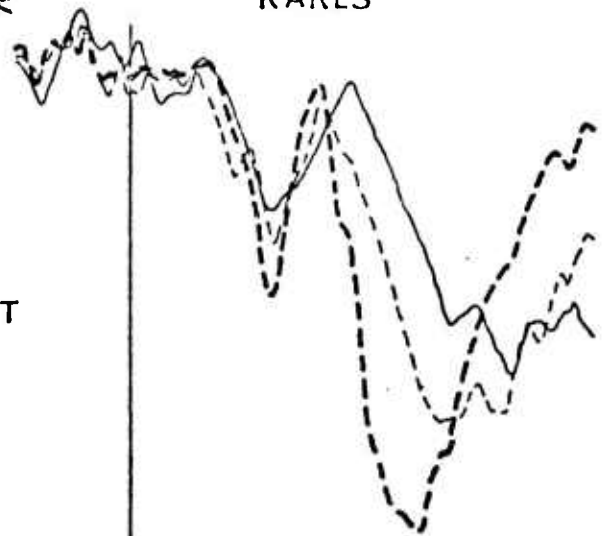
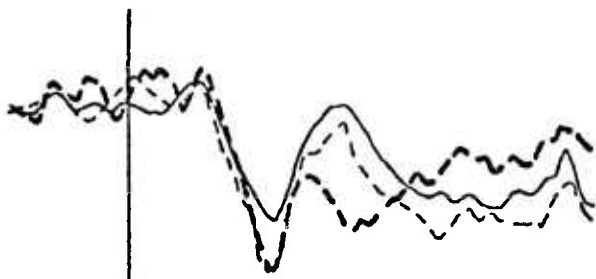
SPEED
CHOICE RT

1000 MSECS

----- FIXED NAMES
 - - - - - VARIABLE NAMES
 _____ SYNONYMS

20 μ V

CZ



ELECTROCORTICAL INDICES OF HEMISPHERIC UTILIZATION*

Donchin, Kutas, & McCarthy

It is well known that electroencephalographic (EEG) activity recorded from widely spaced scalp electrodes is quite diverse; at any instant the voltage at any site may be of a different amplitude or polarity than that recorded at other electrodes. When the properties of the EEG as a time series are evaluated over extended epochs, spectra of simultaneously recorded series vary considerably (Walter, Rhodes, Brown, & Adey, 1966). This variability is due to the structural and functional differences between brain sites underlying the electrodes. As brain tissue varies in its activity patterns so do the manifestations of these activities on the scalp.

The scalp distribution of EEG parameters, estimated from appropriately placed electrodes, has long served to support inferences concerning intracranial electrophysiological events. The most notable success and broadest application of these inferential procedures has been in clinical neurology (Cooper, Osselton, & Shaw, 1974). The scalp distribution of the EEG is widely used in localizing epileptic foci (Gibbs, Lennox, & Gibbs, 1936), tumors (Walter, 1936), focal lesions (Case & Bucy, 1938), and other pathologies. The relative success of these procedures has

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derived from the fact that the pathology may create localized electrical activity at the scalp (Cooper et al., 1974). More recent attempts to identify the intracranial locus of the generators of components of time-locked, event-related potentials (ERPs) have also assumed that these generators represent spatially circumscribed entities (Vaughan, 1969, 1974; Goff, Matsumiya, Allison, & Goff, 1969). In the case of events generated early in the afferent sequence (events we shall label *exogenous*), such inferences seem to be well supported (Goff et al., 1969; Jewett, Romano, & Williston, 1970).

This review is concerned with attempts to extend the use of EEG scalp distribution to the assessment of the differential utilization of distinct cortical areas under different circumstances. Our review is restricted to studies that compare the electrical activity recorded from homologous sites on the two hemispheres. The data collected in these studies are normally used to infer which of the two hemispheres is "utilized," or more actively engaged, during the performance of one task or another (cf. Gur & Gur, this volume).

The use of electrophysiological indices of hemispheric utilization has grown with the increasing interest in the study of the complementary specialization of the hemispheres. Much evidence, surveyed in other chapters of this volume, has accrued during the past two decades demonstrating that the two hemispheres are not functionally equivalent. A grossly oversimplified summary of these data would describe the left hemisphere, in dextrals, as supporting verbal, analytic processing, and the right hemisphere as specializing in spatial, holistic processing. Although the association between speech and the left hemisphere has been known since at least the mid-nineteenth century (Broca, 1861), the more extensive knowledge obtained during the past two decades has derived primarily from research on more recent populations of commissurotomed (Gazzaniga, 1970; Sperry, 1974), hemispherectomized (Smith, 1972), or lesioned patients (Milner, 1974). Extension of this work depends on complementary and more accessible sources of data. At present the most successful approach has been through the presentation of lateralized sensory inputs (Kimura, 1961, Bryden, 1965; see Berlin; Springer, this volume), which allow, through the use of the standard techniques of experimental psychology, an evaluation of differential hemispheric processing (Diamond & Beaumont, 1974).

Lateralization of sensory inputs, however, is not an easy procedure and imposes numerous restrictions on the range of paradigms in which hemispheric specialization can be studied. It is in this context that the use of electrophysiological techniques is of potential value. If indeed it is possible to infer hemispheric utilization from electrophysiological parameters, then this convenient, noninvasive technique would be available to complement the data obtained from commissurotomed patients.

This chapter is a review of past attempts to realize the

potential contribution of EEG lateralization studies (see also Butler & Glass, 197[^]). As will become apparent, the literature is replete with uncertain and conflicting results often due to inadequate attention to methodology. The chapter concludes with a description of work conducted in our laboratory.

A SURVEY OF CURRENT STUDIES

Virtually all studies reviewed in this chapter have employed the same general paradigm. The independent variable is always defined in terms of tasks assigned to the subject, some presumably involving the right, others the left hemisphere. The dependent variable is always some parameter of the scalp-recorded EEG activity.

The term parameter is used in this paper in the following sense: The primary data collected in all the reviewed studies consist of the raw EEG recorded in either analog or digital form. Any number of functions can be defined on these raw data. Such statistics as the mean power, the frequency spectrum, the cross-correlation function, or the ensemble average are all functions of the raw data, and all estimate some parameter of the process generating the data. Thus, investigators have wide freedom in the choice of parameters. The specific choice they do make is determined by their hypotheses on the nature of the EEG and EEG-behavior relations. The choice, in turn, can determine the import of the results. 9

The studies can be conveniently classified into two categories according to the dependent variables used. In one category are all studies that focus on the "ongoing" EEG activity and in which frequency-domain parameters of the EEG are estimated (see Gardiner & Walter; Nelsen, Phillips, & Goldstein; Webster, this volume). Such parameters are usually measures of the power or amplitude, of the EEG, integrated over some narrow or broad bandwidth. In the second category fall studies that analyze the EEG in the time domain (see Anderson; Stamm, Rosen, & Gadotti; Thatcher, this volume). These are exclusively concerned with the waveforms of event-related potentials (ERPs) extracted from the EEG by signal averaging. Within these two categories the studies are classified in terms of the independent variables used by the experimenter. An overview of the dependent variables follows.

Frequency-Domain Studies of the EEG

Many investigators have compared the distribution of the spectral power of the EEG at homologous hemispheric locations. Best known are studies focusing on the activity in the 8-12 Hz band (known as alpha). The interest in alpha activity derives from the well-known inverse relationship between alpha power and mental effort (Adrian & Matthews, 1934; Berger, 1930). The assump-

tion is made that hemispheric involvement might be indexed by differential suppression of alpha in the two hemispheres (Galín & Ornstein, 1972). More recently, measures of intrahemispheric "coupling" have been used as indices of hemispheric utilization (Callaway & Harris, 1974). The assumption here is that hemispheric involvement leads to a greater degree of interaction between different intrahemispheric sites, which manifests itself in increased intrahemispheric coupling.

Time-Domain Studies of Event-Related Potentials (ERPs)

With few exceptions, students of the ERP report their results in terms of amplitude or latency of the entire ERP waveform, or its features. It is important, however, to distinguish between three classes of ERP studies in terms of the components that are in fact analyzed. The ERP consists of a sequence of positive-negative potentials that either precede or follow the eliciting event. Post stimulus activity tends to subside after about 500 msec, though anticipatory processes are known to operate over several seconds. The early poststimulus components represent stages in the afferent stream (Buchwald & Huzar, 1975) and are often referred to as exogenous. Exogenous components can only be recorded in association with some sensory stimulus. Their scalp distribution depends to a considerable extent on the modality of the stimulus (Goff et al., 1969) and their morphology on the physical parameters of the stimulus. 5

By contrast, the later ERP components, those with latencies exceeding 150 msec, can be elicited in the absence of a stimulus (Sutton, Tueting, Zubin, & John, 1967; Klinke, Fruhstorfer, & Finkenzeller, 1968), are relatively insensitive to stimulus modality (Vaughan, 1969), and are enormously sensitive to task parameters. We believe these components are manifestations of cortical information-processing activities engaged by task demands, and we shall refer to these as *endogenous* components (Donchin, 1975).

There are two classes of endogenous components, those appearing before and those appearing after the eliciting events. Of the postevent components, the best known is P300 (Sutton, Brarup, Zubin, & John, 1965). The preevent components, such as the Contingent Negative Variation (CNV) or the Readiness Potential (RP), are apparently related to anticipatory or preparatory activities (Walter, Cooper, Aldridge, McCallum, & Winter, 1964; Kornhuber & Deecke, 1965).

The studies relating ERP components to hemispheric specialization have most often been concerned with endogenous components. However, data on the lateral distribution of exogenous components are available and will be reviewed.

SURVEY OF FREQUENCY-DOMAIN STUDIES

EEG Measures and Handedness

This survey begins with an analysis of the relationship of EEG measures to manual preferences, followed by a discussion of task-induced changes in scalp distribution of EEG parameters.

Early investigators of the EEG, although they noted occasional hemispheric asymmetries, stressed the similarity of EEG tracings recorded from the two hemispheres (Adrian & Matthews, 1934). Large differences between homologous recordings were considered abnormal and were used to localize focal disorders not characterized by obvious dysrhythmias (Aird & Bowditch, 1946; Aird & Zeale, 1951). Much evidence, however, that the alpha rhythm is rarely symmetric in amplitude or in phase has accrued in the past few decades (Raney, 1939; Remond, Leservre, Joseph, Rieger, & Lairy, 1969; Liske, Hughes, & Stowe, 1967; Hoovey, Heinemann, & Creutzfeldt, 1972). These asymmetries have sometimes been related to the subject's lateral preferences. The alpha rhythm in the dominant hemisphere has been found to be of lower amplitude (Cornil & Gastaut, 1947; Raney, 1937), but this relationship is not universally reported (Butler & Glass, 1974a; Glanville & Antonitis, 1955; Liske et al., 1967; Provins & Cunliffe, 1972; Remond et al., 1969). A relationship between interhemispheric EEG phase and laterality preferences has also been reported (Giannitrapani, 1967; Giannitrapani & Darrow, 1963; Giannitrapani, Darrow, & Sorkin, 1964; Giannitrapani, Sorkin, & Ennenstein, 1966). However, the relationship appears to be quite complex and ^{ed}confusing, with the direction of the phase asymmetry changing with subject and state variables.

In part, the confusion derives from difficulty in defining and validating a "resting" state in which to take baseline EEG measures. The wide variations in measurement and analysis techniques also account for some of the confusion in the literature. Mostly, however, the relationship between EEG laterality and subjects' lateral preferences is in fact quite complex. Inter-hemispheric alpha asynchrony has been reported to be more prevalent in subjects with less established lateral preferences, such as the ambidextrous, or in those in whom lateral specialization may be weak, such as stutterers (Travis & Knott, 1937; Lindsley, 1940). Similar asynchronies have also been found in children with disordered verbal-motor development (Lairy, Remond, Rieger, & Leserve, 1969). Amplitude asymmetries, on the other hand, have been reported to be larger in subjects with clearly defined hand preferences (Lairy et al., 1969; see Subirana, 1969). EEG measures may, then, depend on the degree of lateral specialization in individuals rather than on its direction (cf. Collins, this volume). Such considerations must be kept in mind when evaluating the use of EEG measures to index functional asymmetry in the human brain.

Interhemispheric EEG Asymmetries and Hemispheric Specialization

A number of recent studies have claimed that interhemispheric changes in alpha and total EEG power accompany the performance of functionally asymmetric tasks. Such investigations typically employ a paradigm in which a subject performs a task thought to engage primarily one hemisphere while bilateral samples of EEG are taken. Occipital (Dumas & Morgan, 1975; Morgan, Macdonald, & Hilgard, 1974; Morgan, McDonald, & Macdonald, 1971), temporal and parietal (Doyle, Ornstein, & Galin, 1974; Galin & Ornstein, 1972; McKee, Humphrey, & McAdam, 1973) electrode placements, referenced to the vertex (C_z) position, have been used. Intrahemispheric bipolar linkages have also been employed (Butler & Glass, 1974a).

Tasks presumed to utilize the left hemisphere differentially have included composing letters (Galin & Ornstein, 1972; Doyle et al., 1974), word-search tasks (McKee et al., 1973), mental arithmetic (Morgan et al., 1971, 1974; Dumas & Morgan, 1975; Butler & Glass, 1974a), and verbal listening (Morgan et al., 1971, 1974; Dumas & Morgan, 1975). Right-hemisphere tasks have included modified Kohs Blocks, Seashore tonal memory, and drawing tasks (Galin & Ornstein, 1972; Doyle et al., 1974). They have also included spatial imagery tasks (Morgan et al., 1971, 1974; Dumas & Morgan, 1975) and music listening tests (McKee et al., 1973; Morgan et al., 1971; see Gardiner & Walter, this volume). In addition, occupation (artist versus engineer) and hypnotic susceptibility have been used as independent variables (Morgan et al., 1971, 1974; Dumas & Morgan, 1975).

Data have been analyzed in many different ways. Often, investigators have integrated the raw or filtered EEG (Dumas & Morgan, 1975; Galin & Ornstein, 1972; McKee et al., 1973; Morgan et al., 1971; Nelsen et al.; Webster, this volume). Others have computed amplitude histograms of the EEG (Butler & Glass, 1974a) or have used conventional spectral-analysis techniques (Doyle et al., 1974; Gardiner & Walter, this volume). Despite the variety of methods for obtaining estimates of power, most researchers have then expressed their results in terms of right/left or left/right power ratios for homologous electrode sites (Doyle et al., 1974; Galin & Ornstein, 1972; McKee et al., 1973; Nelsen et al.; Webster, this volume) or as a laterality score expressing differences in power as a function of total power (Dumas & Morgan, 1975; Morgan et al., 1974; Gardiner & Walter, this volume). Changes in these ratios are interpreted as evidence for differential hemispheric involvement. For example, Galin and Ornstein (1972) obtained the power of the total EEG at the right and left parietal electrodes. The right/left power ratio is 1.15 for the spatial Kohs Blocks task and 1.30 for the verbal letter-writing task. The increase in the power in the right hemisphere relative to the left hemisphere for the letter-writing task is presumed to reflect the greater involvement of the left hemisphere in that task (recall that increased power implies increased alpha

activity and by inference implies a lesser degree of hemispheric involvement). Similar results were obtained in studies of activity in the alpha band (Dumas & Morgan, 1975; McKee et al., 1973; Morgan et al., 1971). Butler and Glass (1974a) found left-hemisphere suppression of alpha during mental arithmetic but only in their dextral subjects; unfortunately, no right-hemisphere tasks were used for comparison. A more sophisticated frequency analysis (Doyle et al., 1974) revealed that the main locus of task-dependent distributional changes occurs in the alpha band. They reported minor interhemispheric differences in the beta and theta bands and no changes in the delta band (cf. Gardiner & Walter, this volume).

Although these studies may indicate that there are small task-dependent changes in the EEG spectrum, the implication that selective suppression in the dominant hemisphere for the task is the cause of the ratio changes cannot be supported on the evidence presented. It is not possible to tell if a ratio has been modified by changing the numerator, the denominator, or both when only the ratio figure is presented. Note also that in most of these studies the experimentally induced differences are superimposed upon a constant right/left hemisphere asymmetry and do not represent shifts from a symmetric baseline.

Intrahemispheric EEG Measures and Hemispheric Specialization

To date, only one study has employed the intrahemispheric coupling approach to the study of hemispheric specialization (see Livanov, Gavrilova, & Aslanov, 1964, 1973 for related work). Callaway and Harris (1974) reported that appositional or spatial analysis of visual stimuli increases the relative amount of posterior right hemisphere coupling, and propositional examination of visual material (such as reading) increases posterior left hemisphere coupling. As yet unpublished data from the same laboratory tend to confirm and extend these observations (Callaway, personal communication).

SURVEY OF TIME-DOMAIN STUDIES

In this section we report on studies of event-related potentials (ERPs) extracted by signal averaging from the ongoing EEG. All the studies reviewed compared ERPs recorded at homologous hemispheric sites. As in the frequency-domain studies discussed in the previous section, the ERP investigators endeavored to demonstrate that task variables determine the relative amplitude of ERPs over the hemispheres. These differences were sometimes evaluated in terms of subjects' handedness and cerebral dominance.

Studies of Exogenous Components

Very few of the studies reviewed in this section were motivated

by an interest in hemispheric specialization. Rather, the investigators were seeking information on the scalp distribution of sensory evoked potentials. Their goal has usually been the elucidation of the intracranial sources of these exogenous components. Yet data were often collected from homologous hemispheric sites. These provide valuable baseline data on hemispheric asymmetries. Clearly, if ERPs associated with a given modality are asymmetric in the absence of any task inducement for such lateralization, such biases must be considered when testing hypotheses about hemispheric specialization. The results on hand, however, are equivocal. It would be difficult to develop, on the basis of the available literature, a specification of the lateralization biases for different stimulus modalities.

Somatosensory ERPs

The data are scant. The consensus seems to be that the largest somatosensory responses are recorded from the scalp overlying the parietal cortex contralateral to the stimulation site (Calmes & Cracco, 1971; Goff, Rosner, & Allison, 1962; Manil, Desmedt, Debecker, & Chorazyna).
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Auditory ERPs

Considerable controversy exists regarding the lateral distribution of the various components of auditory ERPs. The maximal contralateral projection to the auditory cortex as well as the oft observed dominance of one ear over the other in dichotic-listening tasks (see Anderson; Berlin; Springer, this volume) suggest that, at least under certain conditions, different auditory ERPs should be recorded over the two hemispheres. Most investigators concur that right- and left-ear stimulation generate different scalp distributions, but there is no agreement on the specifics of these distributions. Most reports maintain that there is a general predominance of the contralateral response; some find differences in terms of a shorter latency response (Majkowski, Bochenek, Bochenek, Knapik-Fijalkowska, & Kopec, 1971), others in terms of a larger amplitude response (Andreassi, De Simone, Friend, & Grotta, 1975; Peronnet, Michel, Echallier, & Girod, 1974; Price, Rosenblut, Goldstein, & Shepherd, 1966; Ruhm, 1971; Vaughan & Ritter, 1970), and a few in terms of both these measures (Butler, Keidel, & Spreng, 1969). Vaughan and Ritter (1970) reported a small but consistent tendency for larger responses to appear contralateral to the stimulated ear, but the effect was greater over the left hemisphere in response to right-ear stimulation. Other researchers (Peronnet et al., 1974; Ruhm, 1971) report that the right-hemisphere response is consistently larger only for left-ear stimulation. Peters and Mendel (1974) failed to find such a consistent relationship between the ear stimulated and the latency and amplitude of early (less than 70 msec) ERP components. Given these contradictions, there seems to

be little basis yet in trying to relate the lateral asymmetry of auditory ERPs to handedness, cerebral dominance, or ear preference.

Visual ERPs

Similar inconsistencies appear in studies of the laterality of visual ERPs. Studies of interhemispheric differences in visual ERPs have been particularly hampered by the need to assure that the ERP elicited by stimulation of a retinal half-field is generated entirely within a single hemisphere. Whereas it has been well established that stimulation of different visual half-fields elicits different scalp distributions (see MacKay, 1969; Regan, 1972), the comparison of the hemispheric distributions of visual ERPs is not as straightforward. Several investigators (Kooi, Guvener, & Bagchi, 1965; Vaughan, Katzman, & Taylor, 1963; Harmony, Ricardo, Fernandez, & Valdes, 1973) have reported that visual ERPs recorded over homologous regions in normal subjects are symmetric. Other researchers, however, have maintained that visual ERPs recorded from the right hemisphere are larger than those recorded from the left hemisphere (Perry & Childers, 1969; Rhodes, Dustman, & Beck, 1969; Rhodes, Obitz, & Creel, 1975; Richlin, Weisinger, Weinstein, Giannini, & Morganstern, 1971; Schenkenberg & Dustman, 1970; Butler & Glass, 1972). A more recent report has indicated that retinal site of stimulation may induce latency asymmetries in ERP components (Andreassi, Okamura, & Stern, 1975).

The few investigations (Culver, Tanley, & Eason, 1970; Eason, Groves, White, & Oden, 1967; Gott & Boyarsky, 1972) concerned with the relations between handedness, cerebral dominance, eye dominance, and visual ERPs have yielded ambiguous results. Eason et al. (1967) originally reported that the visual ERPs were larger over the right than the left hemisphere for left-handers only. However, a subsequent report from the same laboratory (Culver et al., 1970) failed to confirm this finding. Rather, Culver et al. reported that visual ERP amplitudes were larger over the right than the left occipital lobe in response to left- but not right-visual-field stimulation. This failure to replicate previous results is attributed by Culver to confounding effects of sex and handedness (cf. Gur & Gur, this volume). Gott and Boyarsky (1972) reported that left-handers produced larger visual ERPs over the left hemisphere and that direct stimulation of the dominant hemisphere (generally right for sinistrals and left for dextrals) elicited ERPs with shorter latency than those elicited by stimulation of the opposite, nondominant hemisphere.

A report by Galin and Ellis (1975) indicates that the symmetry of the visual ERP is influenced by the spectral characteristics of the EEG at the time of stimulus presentation. They found that ERPs elicited during tasks inducing hemispheric asymmetries in alpha power were also asymmetric as determined by measures of

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peak-to-trough amplitude and power. Such results are provocative and suggest that baseline symmetry in ERPs may depend on variability in ongoing EEG activity, which may in turn depend on subject state variables.

Studies of Endogenous Components

Asymmetries in Movement-Related Potentials

The most consistent observations of functionally interpretable lateralization have been obtained for slow potentials that are apparently associated with the control or the monitoring of movement.

1. *Readiness Potential*. There is now a general consensus that the slow negative shift preceding voluntary arm and hand movements, variously called the readiness potential (RP), Bereitschaftspotential (BSP), or N1 of the motor potential (MP), is a few microvolts larger over the pre-Rolandic area on the scalp contralateral to the responding limb (Gilden, Vaughan, & Costa, 1966; Kutas & Donchin, 1974a, 1974b; Vaughan, Costa, & Ritter, 1968). Kornhuber and his co-workers (Deecke, Scheid, & Kornhuber, 1969; Kornhuber & Deecke, 1965) maintain that this contralateral dominance is restricted to the abrupt negativity just preceding the movement, but Kutas and Donchin (1974a, 1974b) demonstrated that the hemispheric asymmetry can be observed hundreds of milliseconds prior to the response. The exact timing of the components of the motor potential immediately preceding the movement is, however, controversial. Gerbrandt, Goff, and Smith (1973) claimed that this negativity occurs after movement; Vaughan et al. (1968) found that the RP has a somatotopic distribution and clearly occurs prior to movement. Two reports (Gerbrandt et al., 1973; Wilke & Lansing, 1973) reject the notion that these premovement potentials are associated with a motor command and claim that the potentials are manifestations of the activity of postresponse proprioceptive mechanisms. However this issue is resolved, there is no question that N1 precedes the movement. Thus, our demonstration that the N1 component of the MP is larger contralateral to the responding hand is a clear illustration of the manner in which EEG scalp distributions reflect hemispheric utilization (Kutas & Donchin, 1974a).

The absolute amplitude of the motor potentials depends on a number of variables such as force (Kutas & Donchin, 1974a, 1974b; Wilke & Lansing, 1973) and motivation (McAdam & Seales, 1969). The relevant parameters affecting the degree of N1 asymmetry, other than subject handedness and responding hand, have yet to be determined. A promising source of data is intracerebral recording from human patients (see McCallum & Papakostopoulos, 1974). These preliminary data suggest that subtle changes in timing and asymmetry of the RP may be obscured in scalp recordings.

2. Response Variables and the Contingent Negative Variation.

Many investigators have noted the similarity of the CNV and N1. The suggestion that these two waveforms might represent identical processes is derived partly from the fact that most CNV studies have required a motor response to the imperative stimulus. Early mapping studies (Cohen, 1969; Low, Borda, Frost, & Kellaway, 1966) demonstrated that the CNV preceding a motor response in an RT paradigm is symmetrically distributed over the two hemispheres. Within the past few years it has been asserted that slightly larger CNVs appear over the hemisphere contralateral to the hand used for the response (Syndulko, 1969, 1972; Otto & Leifer, 1973). Syndulko (1972) reported that this response-related lateral asymmetry was specific to central as opposed to frontal, parietal, or occipital locations and developed only preceding unimanual response preparation. Otto and Leifer (1973), on the other hand, noted that a CNV laterality was statistically significant only when the data were pooled across their response and feedback conditions. It has been well established that CNVs can be generated, in the absence of a motor response (Cohen & Walter, 1966; Donchin, Gerbrandt, Leifer, & Tucker, 1972; Donchin, Kubovy, Kutas, Johnson, & Herning, 1973; Low et al., 1966) and must therefore represent more than mere motor preparation. The weak laterality of the slow negative wave in response-oriented CNV paradigms suggests that the negativity is multiply determined. It is conceivable that both a response-related lateralized negativity and a "cognitive" bilateral negativity are generated in the classical CNV paradigms. Such a two-component hypothesis has been suggested by Hillyard (1973; see also Gazzaniga & Hillyard, 1973). In one of our studies (Donchin, Kutas, & McCarthy, 1974, discussed in more detail later in this chapter), we were able to elicit in rapid succession a lateralized motor potential followed by a bilateral anticipatory potential. (See also Stamm et al., this volume.)

ERP asymmetries Associated with Cognitive Functions

Very few studies have been designed specifically to seek concomitants of lateralized perceptual or cognitive functioning in such endogenous ERP components as P300 and CNV. It has been claimed that the lateral distribution of the CNV changes with task demands, but there is no consensus as to whether the engaged hemisphere has the larger or smaller CNV. Marsh and Thompson (1973) originally observed a symmetric CNV during preparation for a visuospatial discrimination, presumably a right-hemisphere task. When this nonverbal task was randomly interspersed among verbal stimuli and required a pointing (rather than a verbal) response, the hemisphere primary for that task had the smaller amplitude CNV. In contrast Butler and Glass (1974b) found a larger CNV over the dominant hemisphere during a warning interval in which subjects awaited numerical information. The CNV asymmetries took

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the form of an earlier onset and greater amplitude potential over the hemisphere contralateral to the preferred hand. Unfortunately, they had only one left-hander against whom to compare the data of their right-handed subjects. The fact that in their "control" condition large asymmetric CNVs were also generated makes the results still more difficult to interpret. Care must in general be exercised in the choice of stimulus modalities and response requirements in designing such studies, as CNVs in different paradigms have distinct anterior-posterior scalp distributions, a central dominant CNV preceding tasks requiring motor readiness (Jarvilehto & Fruhstorfer, 1970; Syndulko, 1972; Poon, Thompson, Williams, & Marsh, 1975), a frontal dominant CNV accompanying auditory discrimination (Jarvilehto & Fruhstorfer, 1970; Syndulko, 1972), and a parietal dominant CNV accompanying similar visual tasks (Cohen, 1973; Syndulko, 1972). No definite conclusions can be drawn at this time as to how CNV distribution is related to cerebral dominance.

In summary, a start has been made toward using ERP methods to investigate differences between the dominant and nondominant hemispheres, but progress has been slow and somewhat hampered by inadequate experimental design and analysis procedures.

ERP Asymmetries in Linguistic Processing

In this section we will review studies of the ERP relating hemispheric asymmetries to linguistic functions. Given the abundant evidence that verbal information is processed more efficiently by the left hemisphere, the search for ERP correlates of linguistic processing has become increasingly energetic in the past decade.

1. *Asymmetries in Language Reception: Visual Modality.* Results based on multiple electrode recordings have led to the claim that asymmetric cerebral functions underlying evaluation of visual stimuli are reflected in the ERP (see Thatcher, this volume). Buchsbaum and Fedio (1969) have presented different visual stimuli (words, dots, or designs) in a random sequence. They reported that ERPs elicited by words can be differentiated from ERPs elicited by nonlinguistic, patterned stimuli. They also claimed that foveally presented verbal and nonverbal stimuli elicit waveforms that are more differentiable when recorded at the left than when recorded at the right hemisphere. They have reported similar results in a study investigating interhemispheric differences in ERPs related to the perception of verbal and nonverbal stimuli flashed to the left or right visual fields (Buchsbaum & Fedio, 1970).

Marsh and Thompson (1973) investigated the possibility that verbal sets would lead to differential right- and left-hemisphere amplitudes of slow negative shifts by asking subjects to identify their stimuli verbally. During the anticipation of flashed words, symmetric CNVs were generated at the midtemporal and angular

gyrus placements. Preliminary data obtained when the two experimental conditions (verbal and nonverbal) were intermixed yielded asymmetries in the temporal and parietal sites. Other studies dealing with visually presented words have noted a striking lack of hemispheric asymmetry. Shelburne (1972, 1973) recorded visual evoked potentials to three individually flashed letters that comprised either a real or a nonsense word. A comparison of the responses elicited by these two different linguistic stimuli revealed no consistent differences between the visual ERPs to the words and to the nonsense syllables in either the left or right, parietal or occipital leads. In a similar paradigm, in which subjects were asked to report the key word in a visually presented sentence, no asymmetries in any of the components of the ERPs associated with words could be seen (Friedman, Simson, Ritter, & Rabin, 1975). Friedman and his associates present a trenchant critique of the studies reviewed in this section.

2. *Asymmetries in Language Reception: Auditory Modality.* Although still contradictory and inconsistent, somewhat more promising results have been obtained with auditory stimuli (Brown, Marsh, & Smith, 1973; Cohn, 1971; Matsumiya, Tagliasco, Lombroso, & Goodglass, 1972; Molfese, Freeman, & Palermo, 1975; Morrell & Salamy, 1971; Neville, 1973; Teyler, Harrison, Roemer, & Thompson, 1973; Wood, Goff, & Day, 1971; Anderson, this volume). A number of studies have in fact supported the view that linguistic analysis occurs primarily in the left hemisphere. In a brief report, Cohn (1971) tells of a prominent, positive-going peak with a 14-msec latency elicited in the right hemisphere by click stimuli but not by single-syllable words. Morrell and Salamy (1971) found the N100 component elicited by nonsense words larger over the left than the right temporoparietal area. It is difficult to interpret their results, as they failed to use a nonlanguage control. Matsumiya et al. (1972) reported a hemispheric asymmetry in a "W-wave" (a positive response recorded bipolarly, peaking at 100 msec) elicited by real words and environmental sounds. They ascribe this hemispheric asymmetry to the significance of the auditory stimuli for the subject rather than to the linguistic features of the stimulus. Wood et al. (1971) reported differences in the ERPs recorded over the left hemisphere that appeared in the N100-P200 component, depending on whether the subject was required to perform a linguistic or an acoustic analysis of the stimulus (cf. Anderson, this volume). Molfese et al. (1975) found a similar enhancement in the amplitude of the N1-P2 component of the ERP in the left relative to the right hemisphere for speech stimuli, even when the subject's task was merely to listen. On the other hand, nonspeech acoustic stimuli were found to produce larger amplitude responses in the right hemisphere. Although Molfese et al. found asymmetries in the auditory ERPs from infants, children, and adults, they noted that the lateral differences to both types of stimuli decreased with age. Neville (1974) reported lateral ERP amplitude and

latency differences elicited by digits but not by clicks is a dichotic listening paradigm. n

Several investigators have attempted to evaluate the influence of linguistic meaning on scalp ERPs. Teyler et al. (1973) reported that different ERPs could be recorded from the same electrode site to the same click stimulus depending on the meaning of the verbal context (noun-verb) to which the stimulus was temporally related. Linguistic stimuli elicited responses of greater magnitude in the dominant hemisphere. In a similar study, Brown et al. (1973) recorded ERPs to the actual words rather than to coincidental clicks. The words they used were ambiguous and were disambiguated by their context. They reported (1) that the waveform of the ERPs evoked by a particular word differed according to its contextual meaning and (2) that these differences were significantly greater for left- than for right-hemisphere loci. It seems then that different investigators find in a variety of ERP parameters greater variability over the left than over the right hemisphere.

3. *Slow-Potential Asymmetries Preceding Language Production.* Whereas the studies just reviewed were primarily concerned with demonstrating different degrees of hemispheric asymmetry in response to verbal and nonverbal stimuli, others have tried to find the ERP concomitants of speech production. McAdam and Whitaker (1971) observed a small increase in the negativity over Broca's area (in the left hemisphere) preceding spontaneous spoken words but not preceding simple oral gestures. This report, however, has been attacked by Morrell and Huntington (1971) on several grounds. They questioned McAdam and Whitaker's procedures, analyses, and conclusions. Morrell and Huntington claim that when movement artifacts were monitored and the same measurements were made for all waveforms, no hemispheric asymmetries consistent with localization over Broca's area could be found (cf. Anderson, this volume). McAdam and Whitaker's findings, on the other hand, have been essentially confirmed by Low, Wada, and Fox (1974, 1976) who, in addition, found a significant correlation between hemispheric dominance as determined by the Wada sodium amytal test and dominance derived from the relative CNV amplitudes in the left and right motor speech area. Zimmerman and Knott (1974) applied similar procedures to an investigation of the physiological basis of stuttering. A comparison of CNVs in stutterers and normal speakers during speech and nonspeech tasks revealed that only 22% of the stutterers showed a left-greater-than-right asymmetry as opposed to 80% of the normal speakers. Thus, although a substantial amount of clinical data supports the theory of left-hemisphere superiority in language reception and production, the ERP data regarding this functional asymmetry are far from consistent. The methodological and statistical shortcomings existing in many of the studies cited render any decision about the efficacy of ERPs as indices of linguistic processing inconclusive.

METHODOLOGICAL CRITIQUE OF LATERALIZATION STUDIES

One need not be overly critical to conclude from the preceding review that it is premature to advocate the use of the EEG and ERP parameters as indices of hemispheric utilization; similar conclusions have recently been adumbrated by Friedman et al. (1975) and by Galambos, Benson, Smith, Schulman-Galambos, and Osier (1975). Yet, within the welter of conflicting claims and apparent inconsistencies there is a thread of positive results that indicates the promise of the approach. The expectation that differential hemispheric utilization will manifest itself in scalp-recorded electrical activity is plausible. When then is the literature so confused? There are two related answers. The functional significance of electrocortical "macro" potentials is, as yet, obscure. Although the evidence is strong that the EEG is a manifestation of "real" brain events, neither its general role, nor the role of its many different parameters has been clarified. It is, therefore, the case that the studies reviewed earlier, as well as our own studies, are not guided by a specific theoretical view of the EEG. On the whole, investigators do not have a priori expectations regarding the direction of the differences they will observe. Until neurophysiologists supply a coherent view of the EEG, an empirical approach must predominate in this research. As long as it does, a measure of uncertainty will naturally pervade the literature.

The uncertainties and confusions deriving from our meager understanding of the EEG are exacerbated by inattention to proper methodology. Even within the constraints discussed previously, the issues could be clarified, were investigators to attend more carefully to methodological considerations. The following is a review of some of the more important points that should be considered in designing, conducting, and analyzing experiments in this field.

It would help to discuss first the formal structure of the experiments reviewed and to identify within that structure the major loci of methodological difficulty. The dependent variable in the reviewed literature is always the difference between a pair of values of some EEG or ERP parameter recorded at homologous bilateral sites. The independent variables are most often discussed in terms of the tasks the investigator has imposed on the subject. A class of tasks that is presumed, on previous data or intuitive grounds, to engage differentially one hemisphere or the other, is usually selected. The experimental conclusions can invariably be stated as a functional relationship between the sign and magnitude of the EEG parameter and task variables, which are in turn presumed to reflect basic features of human information processing.

Assume, for the sake of argument, that there really is a difference of the type sought. If the various experimental statements are in conflict or are not very convincing, any or all of

the following reasons might be the cause:

1. The experimental design is not sufficiently sensitive to allow detection of the differences or is inadequate to support the conclusions.
2. The tasks assigned the subject may not in fact differentially engage the hemispheres.
3. The effects are range-restricted and the values of the independent variables are out of the relevant range.
4. Subject individual-difference variables are not considered.
5. The parameters of the EEG used as dependent variables were unwisely selected.
6. The measurement techniques used to obtain the parameters are inappropriate.
7. The data are improperly quantified and were inappropriately or insufficiently analyzed.

Design and analysis problems in recording scalp electrical activity in humans have been the topic of many comprehensive reviews (Donchin, 1973, 1975; Donchin & Lindsley, 1969; Thompson & Patterson, 1974). Our discussion is therefore limited to those problems specific to the use of the distribution of scalp potentials as an index of hemispheric functioning.

SURVEY OF METHODOLOGICAL PROBLEMS

Design Problems

If one point emerges with clarity from the studies reviewed, it is this: If there are any differences between the electrocortical activity of the two hemispheres, they will be minute. This implies that to reveal lateral dominance for study one must use techniques with the required high resolving power. The subtlety of the differences sought dictates the use of experimental designs of great sensitivity. Real but minute differences should not be ignored (type II errors), but at the same time artifactual sources of interhemispheric differences that may lead to type I errors should be avoided. The designs should minimize the chances of both types of errors. All too often the designs used in the reviewed studies were far from optimal.

In virtually all the reviewed studies, data were obtained from all subjects under all experimental conditions. For example, all subjects were challenged with spatial and verbal tasks. The investigators then chose between pooling the subjects' data, comparing group means, or using a repeated measurements design (with each subject serving as his own control). The last procedure is customarily preferred when large individual differences are expected in the data. The increased power of within-group designs aids in uncovering small-magnitude changes that would otherwise be obscured in between-group variance. Repeated-

measures designs are common in ERP work, but many of the widely cited studies of frequency-domain parameters contain data that were averaged over groups of subjects.

It is, of course, crucial to ensure that all experimental designs include proper control procedures. When lateral asymmetry is attributed to the specific effects of a task, it is incumbent upon the experimenter to demonstrate that the same parameter, when estimated during some neutral task, does not display a similar asymmetry (see Thatcher, this volume). At the least, the investigator should demonstrate that the lateral asymmetry can be reversed or modulated with appropriate changes in the task ("double dissociation"); thus investigators should include tasks designed to engage each hemisphere differentially. Unfortunately, many investigators fail to include such elementary controls. It is sometimes difficult to determine whether asymmetries observed in the control conditions are a function of such variables, as handedness, cerebral dominance, ill-balanced electrode placements, or skull thickness. Again, this problem is especially severe in studies of EEG spectra, although large CNV asymmetries too have been reported in a presumably neutral task (Butler & Glass, 1974b). More extensive baseline data should be collected.

Validation of Task Variables

Common to a number of studies reviewed is the lack of attention directed toward the definition and validation of the task variables presumed to be the independent variables. Too many investigators (Brown et al., 1973; Doyle et al., 1974; Galin & Ornstein, 1972; Morgan et al., 1971) merely ask their subjects to imagine relationships or to perform mental operations without objectively verifying that the subjects are in fact following instructions. Even when measurable responses are required of the subject, no systematic presentation or analysis of these behavioral measures is made (see for example Butler & Glass, 1974a; McKee et al., 1973). Many studies leave the reader to wonder whether the subject complied with task demands and, if so, to what degree. The possible influence of task difficulty on these results has often been ignored. The subjective estimates of task difficulty that have been used are difficult to interpret without performance measures (Dumas & Morgan, 1975; McKee et al., 1973; Morgan et al., 1974).

Although negative results are notoriously difficult to interpret, confusion is compounded when EEG data are based on intuitively chosen tasks that have not been validated. Some advantages may be gained by selecting standard neuropsychological paradigms for which differential hemispheric engagement has been assessed (Neville, 1974). It is also important to avoid confounding psychological variables with varying physical parameters of the task-related stimuli. Ample evidence in the literature demonstrates that the characteristics of ERPs are grossly

affected by physical stimulus properties (see Regan, 1972). Several investigators have devised clever strategies for holding the physical parameters of the stimuli constant while varying task variables (for examples, see Brown et al., 1973; Wood et al., 1971).

Range of Operation of the Independent Variables

The subject's tasks are usually chosen with the assumption that the manipulation of the independent variable will engage one hemisphere or the other. If no interhemispheric differences are found, the investigators tend to deduce that electrocortical activity is not related to hemispheric utilization. This may be a rash deduction. It is, in fact, possible for the independent variable to have a strong effect on the laterality of the EEG for values of the independent variable other than those selected for study. Consider, for example, the assertion that the N1 of the MP displays no lateral asymmetry. This is in fact the case when the subject merely presses a switch or makes a light movement with his finger. If, however, the response requires a considerable degree of muscular involvement, lateral asymmetries appear (Kutas & Donchin, 1974a). Similar results were obtained by McCallum and Papakostopoulos (1974) with intracerebral recordings.

We describe, later, data that suggest that increasing cognitive demands likewise accentuate the lateral asymmetries in the CNV. Within the same context, it is important to note that cognitive sets induced by the order in which experimental conditions are presented can influence the range and direction of functional asymmetries (for behavioral data, see Kimura & Durnford, 1974; Kinsbourne, 1973; for application to ERP work, see Marsh & Thompson, 1973).

Subject Variables

It is a truism that one should know as much as is relevant about the present state and past history of the subject. Yet, such variables as age, sex, prior drug ingestion, and amount of sleep, although known to alter the characteristics of brain activity (Perry & Childers, 1969; Shagass, 1972; Regan, 1972), are sometimes ignored in EEG and ERP studies. Of critical importance in investigations of hemispheric specialization is the subject's history of handedness. Many reports concur that sinistrals differ from dextrals in their response to and recovery from cortical damage and in their performance in a variety of behavioral tasks (Hécaen & Ajuriaguerra, 1964; Levy, 1974). Subject performance is affected not only by handedness but also by familial history of handedness (for references see Levy, 1974). Apparently, the functional asymmetry in the recognition of tachistoscopic material (Bryden, 1965; Springer, this volume) and in dichotic listening (Zurif & Bryden, 1969; Berlin, this

volume) is appreciably smaller for individuals with left-handed relatives. Surprisingly, a number of studies of lateralization have failed to consider this aspect of the subjects' handedness (see Levy, this volume).

Assessing subjects' handedness should be the *sine qua non* of all investigations of laterality. However, subjective self-classification of handedness is inadequate as it correlates poorly with questionnaires and motor performance (Provins & Cunliffe, 1972; Satz, Achenbach, & Fennell, 1967). This is especially true for left-handers, who tend to form quite a heterogeneous population and often yield highly variable test results. Our own experience (Kutas, McCarthy, & Donchin, 1975) has been that handedness is difficult to classify and that, as a minimum requirement, self-reports should be supplemented with questionnaires.

Parameters of the Dependent Variable

Of critical importance is the selection of the proper parameters of EEG or ERP activity for the evaluation of task-induced changes. This is partly an empirical process as many parameters may need evaluation. These task-dependent changes may not always reveal themselves in gross measures of overall ERP amplitude or length, or in total EEG power spectra. They often, in fact, appear as small but consistent modulations of specific ERP components or EEG bandwidths (see Gardiner & Walter, this volume). It cannot be overemphasized that the ERP is not a unitary phenomenon, it is, rather, a sequence of independent components that react differentially to experimental variables (Donchin, 1969).

Care must be exercised in creating composite dependent variables based on various measures of EEG or ERP data. For example, interhemispheric ratios or laterality scores derived from power density spectra can provide a good summary statement descriptive of bilateral power relationships, but such ratios can be misused and are often misleading. Ratios presented independently of the data on which they are based (Doyle et al., 1974; Galin & Ornstein, 1972; McKee et al., 1973) leave the reader uncertain whether the changes are caused by differential engagement of the hemispheres by the tasks consistent with the functional asymmetry of the brain, or are due merely to changes in one hemisphere, perhaps reflecting task difficulty. Reassuring statements about the specific locus of change cannot be taken seriously unless supported by data from each hemisphere.

Data Measurement

Whatever the procedure for measuring the parameters of the dependent variable, no interpretable results can be obtained if data are improperly recorded from the scalp. The necessity for a

common reference (either active or inactive) equidistant from the two electrodes being compared cannot be overemphasized. The use of a nonequidistant common reference, such as a single ear (Gott & Boyarsky, 1972), the use of equidistant but separate references such as O_1-A and O_2-A_2 (Buchsbaum & Fedio, 1969, 1970; Culver et al., 1970; Fedio & Buchsbaum, 1971), and the use of intrahemispheric bipolar linkages without a common reference, such as C_3-P_3 and C_4-P_4 (Butler & Glass, 1974a; Matsymya et al., 1972) confound the assessment of hemispheric asymmetry. This problem is especially acute as the reported differences are often a microvolt or less.

A single nonequidistant reference should be avoided, as activity associated with the reference electrode will be unequally represented at the sites of comparison. Different unilateral reference electrodes allow for the possible introduction of systematic artifacts generated at a single reference but mistakenly identified as an asymmetric component. Intrahemispheric bipolar linkages, on the other hand, can mask existing interhemispheric differences, because of the common-mode-rejection characteristic of differential amplification. Although not without problems (Donchin, 1973), linked ears or mastoids and chin or active midline placements avoid most of the difficulties mentioned.

The number of conditions and electrode placements necessary for adequate examination of distributional effects of task variables on ERP components produce too much data to be easily handled by visual inspection or hand-measurement methods alone. Moreover, visual inspection is often inadequate for dealing with subtle differences between complex waveforms. As previously mentioned, marginal asymmetries, although consistent with experimental manipulations, can be washed out by larger, symmetric components (Hillyard, 1973). Also, experimental effects may not always be evident as a measurable peak or trough in the ERP waveform, but may rather be manifest as a modulation of another component.

We employ Principal Components Analysis (PCA) to identify the distinct components of the waveform and to assess their sensitivity to experimental effects (Donchin, 1966, 1969; Donchin, Tueting, Ritter, Kutas, & Heffley, 1975). This procedure provides an objective definition of ERP components and measures their contribution to each waveform with reference to the entire data set. A detailed treatment of the application of PCA to ERP research is beyond the scope of this paper (Chapman, 1973; Ruchkin, Villegas, & John, 1964). Briefly, the ERP waveform can be considered an estimate of the mean vector of a multivariate distribution. The PCA is one technique for decomposing this mean vector into its component vectors. The nature of this extraction procedure allows separate analyses of variance to be performed on derived factor scores to assess the sensitivity of the factors to the experimental variables. Thus, identification and quantification of the experimental effects can proceed in an

objective manner. The use of the technique is illustrated later in this chapter.

Data Analysis

It is commonly acknowledged that exacting data-analysis techniques are essential for the proper evaluation of the effect of experimental manipulations on measures of brain activity. There is certainly no lack of analysis procedures in the literature reviewed; unfortunately, however, the heterogeneity of quantification procedures makes comparisons between laboratories difficult. The ambiguous nature of many of the paradigms as well as the small magnitude of the experimental effects obtained in this type of research should discourage the more liberal approaches to data analysis, which often seem colored by the expectations of the investigator. Fundamental to the statistical evaluation of any data is the measurement of the magnitude and distribution of error variances. The use of grand averaging, qualitative analysis, and multiple univariate analyses can be criticized on several grounds, among them a disregard for the range of variability in the data.

Two forms of data reduction often employed in the analysis of ERPs, grand averaging (averaging waveforms across subjects and/or conditions) and qualitative analysis, give no indication of the real variability in the data. Grand averaging, although a useful means for visually summarizing a multitude of waveforms, should not be used as the sole method of analysis as no estimate of error variance is available. Purely qualitative analyses (e.g., Cohn, 1971) or visual scoring of asymmetry (Butler & Glass, 1974b) are too subject to experimenter bias to be the only method for assessing the influence of independent variables and, of course, do not allow for the evaluation of statistical significance.

Many of the statistical analysis procedures used in the determination of hemispheric asymmetries are not merely inadequate; they are often inappropriate. The comparison of ERP waveforms and EEG power ratios through multiple univariate procedures (Brown et al., 1973; Doyle et al., 1974; Wood et al., 1971) without adjustment for the number of tests being performed can result in misleading conclusions, since the probability of finding spuriously "significant" difference is underestimated (see the excellent paper by Friedman et al., 1975, for a discussion of the Bonferroni test). There are, moreover, multivariate techniques for the analysis of ERPs (such as those referred to previously) that take into account the interdependence of time points and are not subject to the aforementioned criticisms.

SLOW ERP COMPONENTS AND HEMISPHERIC INVOLVEMENT

We now describe studies from our laboratory that were designed to test the proposition that slow, preevent, "anticipatory" waves can be used to index hemispheric utilization. The data provide evidence that scalp-recorded EEG can be used in studies of hemispheric specialization.

These studies were conducted within the general framework of our interest in the endogenous components of ERPs (Donchin, 1975; Donchin et al., 1973, 1975; Rohrbaugh, Donchin, & Ericksen, 1974). The CNV is one of the more prominent of these components ~~in~~ (McCallum & Knott, 1973, 1976). There is no doubt that it is a manifestation of anticipatory processes, sensitive to a variety of behavioral manipulations; yet, it turns out to be strangely intractable to theoretical analysis. Various conflicting interpretations have been put forward (see, for example, McCallum & Knott, 1976). The crux is the degree to which the CNV represents generalized attentional variables (Karlin, 1970) or more specific preparatory processes (Tueting & Sutton, 1973). It has also been difficult to tease out the relative roles of motor and cognitive preparation. The evidence indicates that CNVs can be recorded in the absence of specific, overt, experimenter-directed motor activity (Donchin et al., 1972; Irwin, Knott, McAdam, & Rebert, 1966), yet it is also clear that the CNV is larger when a motor response is required. If motor preparation is an important determinant of the slow potentials, then a lateralized response requirement should lead to a lateralization of the potentials, with larger amplitudes recorded contralateral to the responding hand.

We began by examining data collected for other purposes (Donchin et al., 1973) in a choice reaction time paradigm. A warning tone preceded one of two possible flashes by 1500 msec; the subject was required to respond to one flash with the right hand and to the other with the left hand. In one series of trials, the two stimuli alternated; the subject, therefore, knew the hand with which to respond. In another series, the stimuli were presented in a random sequence and the subject could not predict the hand to be used. Data were recorded from laterally placed electrodes; thus differences in the lateral symmetry of the CNVs obtained in the random and the alternating sequences could be determined. If motor preparation affects these potentials, it should operate during the alternating sequence. A comparison of the cortical activity preceding the subjects' responses averaged separately for each responding hand failed to reveal any lateral asymmetry in either of the experimental conditions (Donchin, Kutas, & Johnson, 1974).

These data were puzzling. According to Kornhuber and Deecke (1965) and Gilden et al. (1966), asymmetric motor potentials precede self-paced motor responses. A replication of these studies was attempted to determine whether a similar asymmetry could be

observed when the warning stimulus was eliminated from the sequence. This attempt also failed. When subjects pressed a button at a self-paced rate with one hand, the potentials recorded from the two hemispheres were virtually identical.

A possible explanation for this failure to replicate came from Otto (personal communication), who reported finding a lateral asymmetry in potentials preceding a multiple finger response. This was in accord with reports that the CNV was largest when greater muscular effort was required (Low & McSherry, 1968; Rebert, McAdam, Knott, & Irwin, 1967). These findings were originally interpreted in terms of the motivational state of the subject, but it may be that response-force per se determines the CNV (or RP) amplitude.

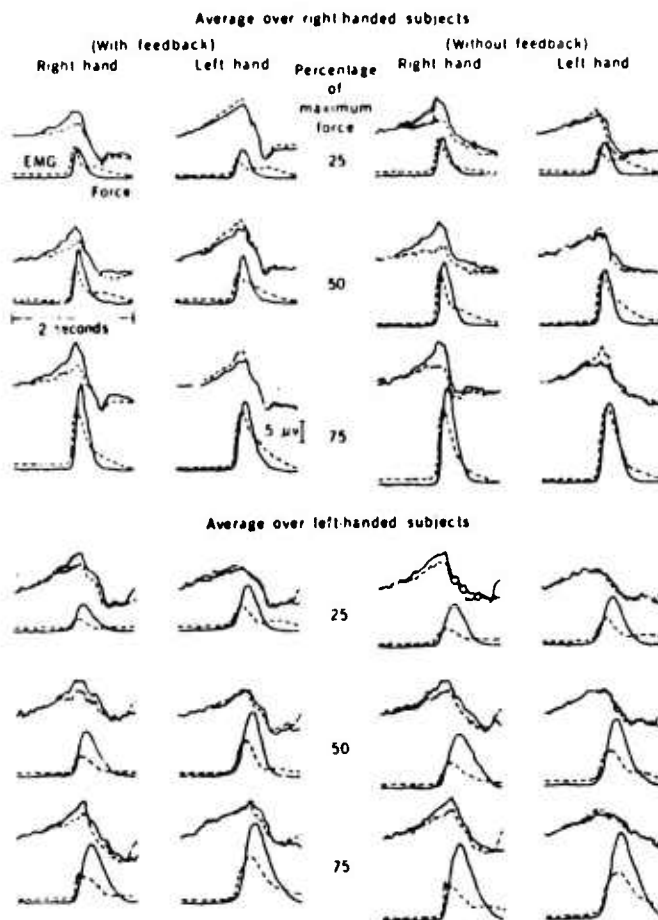
A systematic investigation of the effect of force on the RP was therefore conducted. The lateral distribution of the RP over the motor cortex in both right- and left-handed subjects squeezing a dynamometer with either hand at three levels of force were compared. The force levels were calibrated in terms of the subject's capabilities rather than in absolute terms. In right-handed subjects, the premovement RPs (N1) were larger over the hemisphere contralateral to the responding hand. Left-handed subjects showed contralateral dominance only when responding with their right hands (see Figure 1). An analysis of the N1 magnitude revealed that although response-force does accentuate the motor asymmetry, the absolute right-left asymmetry does not change with increasing force levels (for a more detailed account, see Kutas & Donchin, 1974b).

It turns out, that past failures to demonstrate conclusively the hemispheric asymmetry of the RP may have been due to the range of the independent variable (response-force, in this case) and to an inattention to subject variables. Many reports concerning the RP have failed to mention subjects' handedness, and the few that did mention it failed to consider it in evaluating the data.

A COMPARISON OF READINESS POTENTIAL AND CNVs

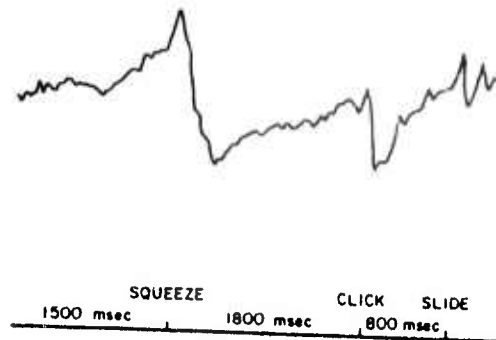
The results described previously led to an investigation of the relationship between the lateral asymmetry of the RP and the CNV (Donchin et al., 1974). Again, subjects were required to squeeze a dynamometer with one hand or the other. In addition, various tests of each subject's lateral preference were administered. After a detailed examination of various tests for handedness (Kutas et al., 1975), we selected the Edinburgh questionnaire (Oldfield, 1971) as an instrument of choice.

In order to make the dynamometer squeeze less tiresome to the subjects, scenic slide presentations were made contingent on dynamometer squeezes that attained a specified force level. Figure 2 presents the sequence of events in an experimental trial. A self-paced squeeze, if "correct," was followed after 1800 msec



Donchin fig 1 55%

Fig. 1. A comparison of event-related potentials (ERPs) recorded at electrodes placed at left-central (C_3 , solid line) and right-central (C_4 , dashed line) loci during voluntary squeezes. Under each pair of superimposed ERPs we have plotted the integrated electromyogram (EMG) (dashed line) and the output of the force transducer (solid line) averaged over the same trials over which the ERP was averaged. Comparisons are presented as a function of subject's handedness (right versus left), nominal force output (25, 50, and 75% of subject's maximal force), responding hand (right versus left) and feedback (presence or absence of visual signal indicating force level). Averages were obtained over all subjects, after the elimination of trials in which the EEG was contaminated by electrooculogram (EGO) activity. Number of trials per ERP ranges between 600 and 1050. The polarity convention is negative up. Hatching in two areas of the comparisons illustrates the areas measured for the purpose of the quantitative data analysis. From Kutas and Donchin, 1974a.



Donchin fig 2 50%

Fig. 2. The sequence of events in an experimental trial. Trial duration was 4500 msec. The waveform drawn above the time line is of the ERP obtained by averaging the entire data set collected from left-handed subjects at a central position. It serves merely to indicate the time of occurrence of the various ERP components.

by an audible click (generated by the mechanism of the slide projector) which was followed after 800 msec by the presentation of the slide. Thus, each trial consisted of three distinct phases: a prereponse interval over which an RP could be recorded, a post response interval, and finally the click-slide interval during which a measurable CNV could be recorded. This paradigm enabled a comparison of the hemispheric asymmetry of the pre-movement RP, which we expected to vary as a function of the responding hand, with the hemispheric symmetry of the CNV. This design thus permitted an examination of the degree to which the asymmetries observed by Kutas and Donchin (1974a) were specific to the premotor interval, or were extended over a long interval. This also allowed for an examination of the possibility that, although the RP is asymmetric, the CNV is symmetric.

In Figure 3 are grand averages for the right- and left-handed subjects, recorded at the frontal, central, and parietal locations. The ERPs recorded at homologous hemispheric sites are superimposed. These averages were obtained by triggering the computer on the dynamometer squeeze. Several aspects of the data are immediately apparent. Clearly, the squeeze is preceded by an RP, which is asymmetric. Moreover, the asymmetry reverses with the responding hand. Following the squeeze, a long-lasting asymmetric slow wave appears, which displays a polarity opposite that of the presqueeze potential. The CNV that follows the click is symmetric, though superimposed on the slow wave. There are substantial differences between the scalp distribution of the CNV and the RP. The CNV is equally large at the frontal and central sites, but the RP is largest centrally. Note also the sharper resolution of the CNV in the parietal sites.

A more detailed look at the data is provided in Figure 4, where waveforms are shown for five individual subjects. The

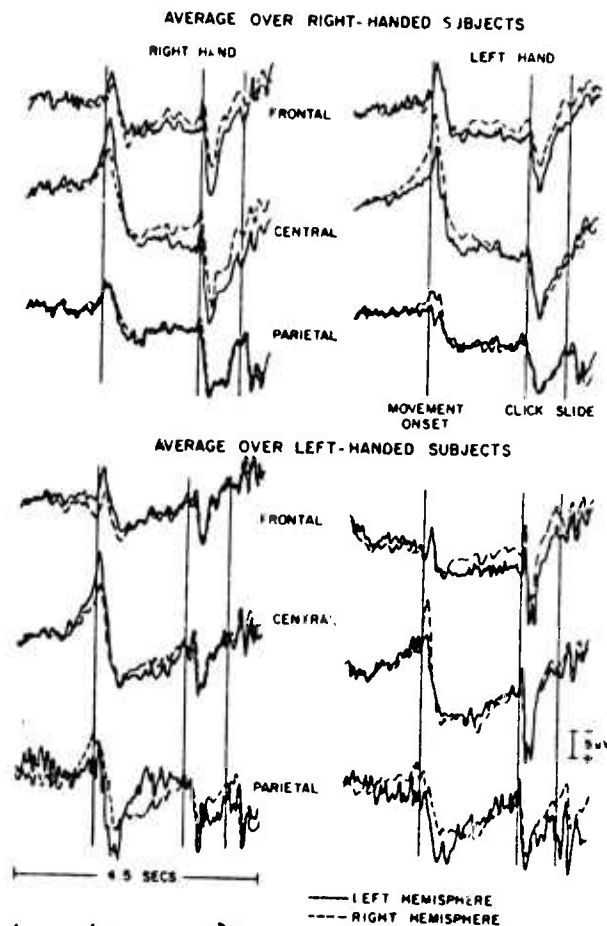


Fig. 3. ERP waveforms recorded from frontal, central, and parietal positions. Data obtained simultaneously from homologous sites are superimposed. There were approximately 75 trials per subject per condition.

curves displayed were obtained by element-to-element subtraction of the ERPs at the right and left central electrodes (these then are equivalent to a "bipolar" recording between the two central electrodes). For each subject, data obtained with right- and left-hand squeezes were superimposed. When the premotor interval is examined, a strong measure of asymmetry is observed. For each subject the potential difference reverses polarity with the responding hand. It is important to note that the degree of polarity reversal is far more evident when intrasubject rather than intersubject comparisons are made. The specific difference waveforms vary considerably from subject to subject, yet within subjects the potentials are of opposite polarity, suggesting a change in the direction of laterality.

No such asymmetries are observable for the CNV. Whereas the postresponse slow potential is quite prominent and seems to

DIFFERENCE CURVES FOR ERPS OBTAINED
WITH RIGHT AND LEFT HAND RESPONDING

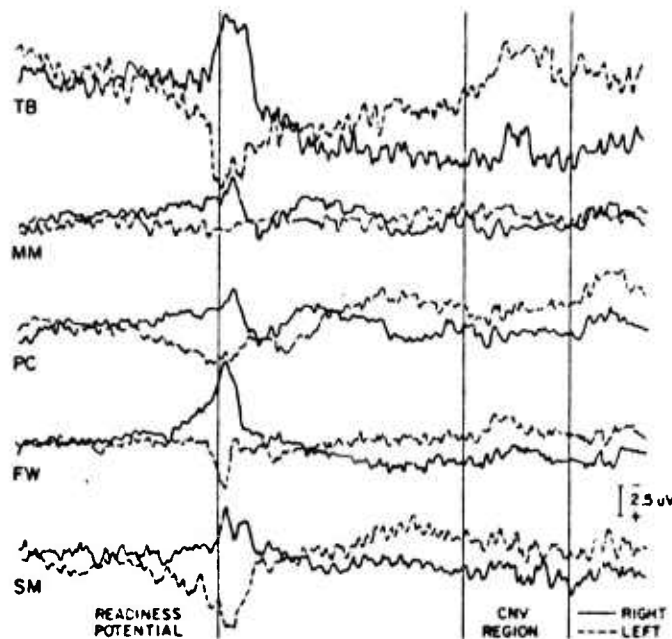
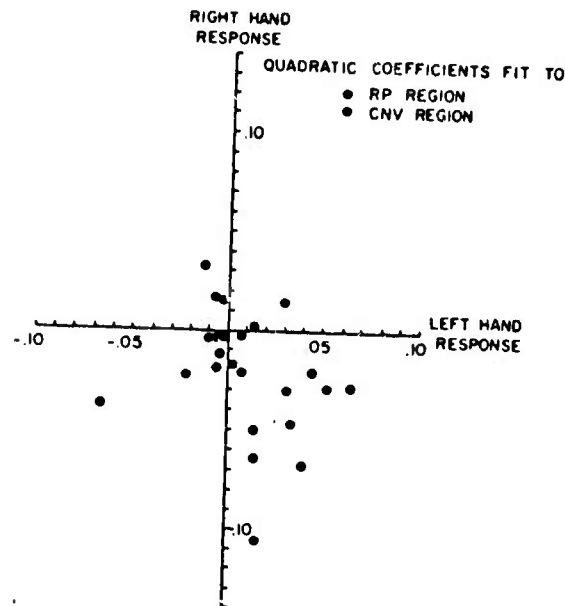


Fig. 4. All waveforms shown in this figure were obtained by point-to-point subtraction of ERPs recorded at the left-central electrode from ERPs recorded at the right-central electrode. This difference will be negative if the left-hemisphere potential is larger, and positive if the right-hemisphere potentials are larger. For five subjects (three dextral and two sinistral) we superimposed data obtained when subjects were squeezing a dynamometer with the right hand (solid line) and the left hand (dashed line). Each waveform represents an average of 75-80 trials. The first vertical line separates pre- from postsqueeze activity; the second and third lines delineate the click-slide interval (CNV).

extend over the entire recorded epoch and probably beyond it, the click-flash CNV is apparently equal in amplitude at both sites. A quantitative statement of this trend is shown in Figure 5. We have fitted a quadratic function to the RP and to the CNV segments of the curve. In Figure 5 is a plot of the coefficients of the quadratic terms that were computed for ERPs associated with right-hand squeezes against coefficients associated with the left-hand squeezes. If the two curves show opposite polarity, the coefficients should be of opposite sign. For the RP, the coefficients are large, and for most subjects the magnitudes of the two coefficients are reasonably similar, but the signs are different. For the CNV, the coefficients are clustered around the origin and show no tendency toward opposite polarity.

These data provide support for the idea that lateral asymmetry can be used as an index of hemispheric utilization. Shifts in



Donchin fig 5 so 2

Fig. 5. Regression coefficients of the quadratic term obtained from a polynomial fit to the premovement (full circles) and CNV (crossed circles) region of the difference waveforms illustrated in Figure 4. Coefficients computed on the basis of right-hand response data are plotted against coefficients obtained when subjects were squeezing with their left hands.

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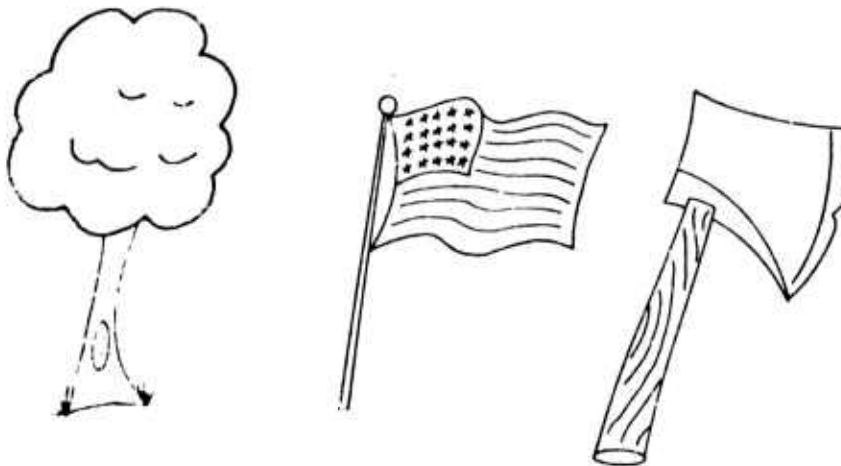
asymmetry appear to be quite rapid and are finely tuned to shifts in the subject's tasks. The nature and significance of the long, slow, postresponse wave is not clear, yet it is obvious that the more rapid shifts in asymmetry can be detected when they are superimposed on such long-term trends. Thus, these data lend plausibility to the "two-factor hypothesis," which views anticipatory negative shifts as a mixture of motor and cognitive preparatory processes (Hillyard, 1973).

LATERAL ASYMMETRIES IN A CNV PARADIGM

Although the data presented in the preceding section demonstrate the differential anterior-posterior and interhemispheric distribution of the RP and CNV, it remains to be determined if the CNV is always symmetric or perhaps, with proper choice of tasks, can be lateralized. Conceivably, just as a forceful squeeze was required to demonstrate the asymmetry of the RP, a stronger cognitive "squeeze" might be required to demonstrate the lateralization of the CNV. An experiment was designed, therefore, to manipulate task variables that might contribute to the formation of an asymmetric CNV.

The task chosen was patterned after the Structure-Function matching task developed by Levy (1974) in her work with commissurotomized patients. One of two warning tones (1000 Hz or 2000

Hz) preceded, by 1000 msec, a brief (50 msec) presentation of a slide. Each slide contained three figures, two of which formed a structural or "look-alike" match (right-hemisphere-dominant task) and two of which formed a functional or conceptual match (left-hemisphere-dominant task). Both types of matches could be made from each slide with one figure common to the two matches (see Figure 6). Subjects responded by pressing one of three



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Fig. 6. One of the 42 slides used in the study. The ax and the tree are functionally matched; the ax and the flag are structurally matched. If cued to make a functional match, the subject would respond by pressing a button with the second finger of his right hand. For a structural match, the subject would press a button with the third finger.

buttons (with one of three fingers of the right hand) coded for the three possible figure combinations. Subjects were instructed to respond as quickly as possible following the slide presentation. Reaction time (RT) and the subject's choice were recorded for each trial along with 2000 msec of EEG from a nine-electrode montage (F_3 , F_4 , C_3 , C_4 , P_3 , P_4 , F_2 , C_2 , P_2 --according to the 10-20 system for electrode placement). The vertical electrooculogram (EOG) was recorded on a separate channel. Trials associated with eye movements were excluded from analysis. Recording of the EEG data began 200 msec prior to the warning stimulus. (For data-acquisition procedures see Donchin & Heffley, 1975.)

Two general experimental conditions were used. In *fixed-match* series the warning tone was the same on all trials in a run, the subject making the same match on each trial. In *mixed-match* series, the tones varied randomly from trial to trial, and the required match varied accordingly. For each subject each tone pitch was always associated with one match type. An additional series was used in which the subject was instructed to respond by

using a single response button to all slides. Results were obtained in a pilot study of five female subjects, all dextral (as verified by the Edinburgh Inventory, Oldfield, 1971) and all without sinistral relatives.

The reaction times and matching errors are presented in Figure 7. It is apparent that both measures differ significantly as a function of task. These data establish that the two tasks placed different demands on the subjects. This does not, of course, prove that the two tasks engaged the hemispheres differently.

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PERFORMANCE DATA FOR EACH EXPERIMENTAL CONDITION

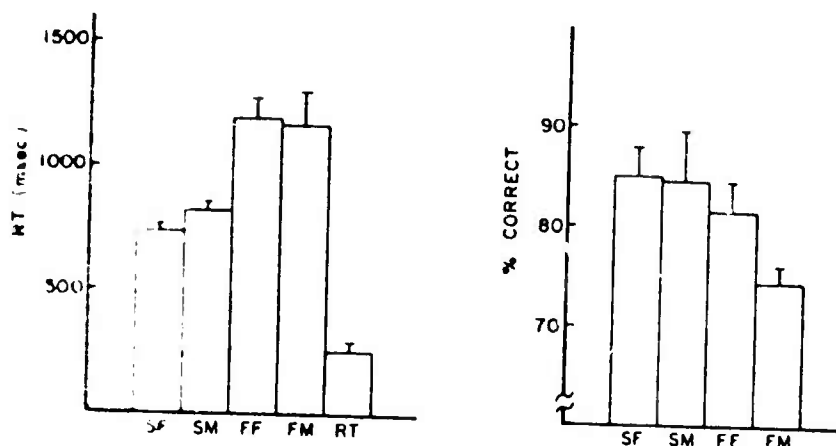
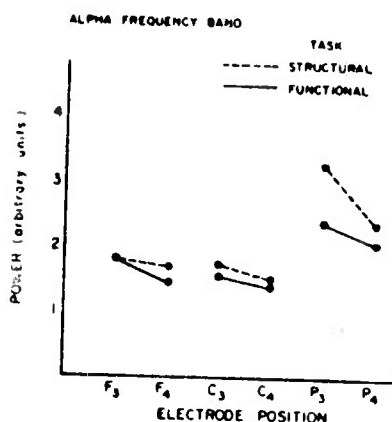
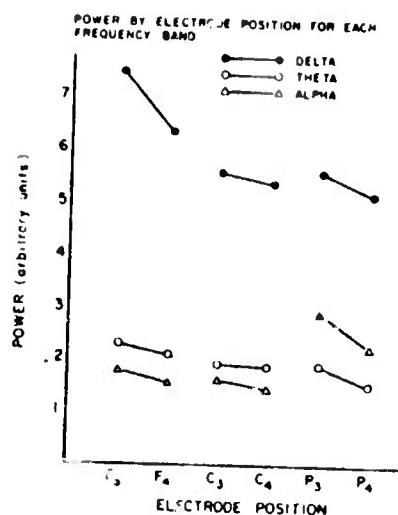


Fig.

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 in reaction time ($p < .0005$, $F = 21.66$, $df = 1,16$) and in percentage correct ($p < .048$, $F = 4.57$, $df = 1,16$) between structural and functional matching are significant. Abbreviations: SD, structural/fixed-match condition; SM, structural/mixed-match; FF, functional/fixed-match; FM, functional/mixed-match; RT, baseline reaction time to signal with no match required.

Hemispheric engagement was assayed by spectral analysis of the single-trial EEG data. It was necessary to determine if changes in the distribution of power within the delta (1-3.5 Hz), theta (4-7.5 Hz), and alpha (8-12 Hz) bandwidths accompanied performance of the tasks. The data analyzed were the 2000-msec epoch, which included 1200 msec of preslide EEG as well as 800 msec of data taken while the subject was actively performing the task. Figure 8 (top frame) presents the distribution of power within each frequency band. An analysis of variance of power measures at each band was performed to determine if the nature of the matching task affected the scalp distribution of the power. Our data indicated that, within the alpha bandwidth only, the tasks differentially affected the distribution of power, primarily at the parietal electrode sites ($p < .03$; $F = 2.97$, $df = 5,20$). There is relatively less alpha activity (see Figure 8, bottom

(8-12 Hz)



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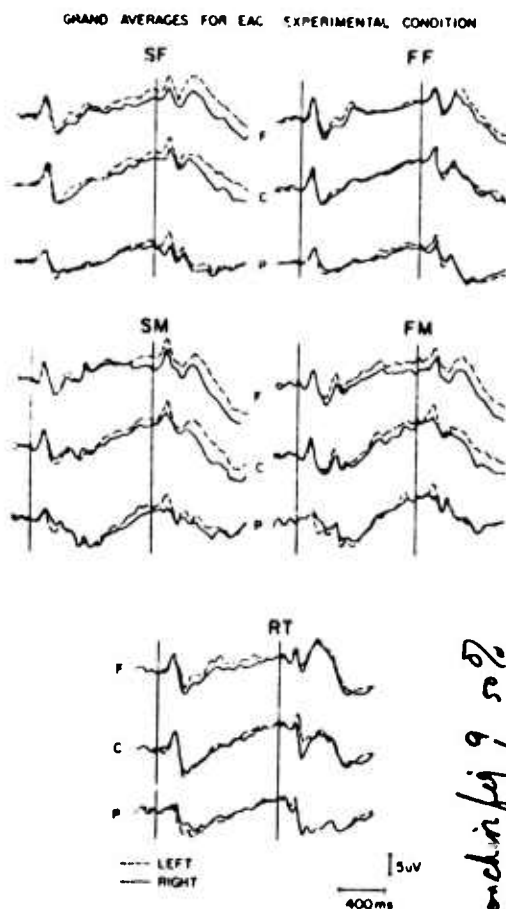
Fig. 8. Top: Distribution of the mean power for the delta (1-3.5 Hz), theta (4-7.5 Hz), and alpha (8-12 Hz) bands is shown for left and right frontal (F₃, F₄), central (C₃, C₄), and parietal (P₃, P₄) electrode sites. The data for analysis were obtained from the fixed-structural or functional-match conditions. Data from 15 trials in which the subject responded correctly were used for each analysis. Bottom: the task by electrode interaction for power and the alpha band. The power associated with functional matching is lower at all electrode positions than the power associated with structural matches. The difference, however, is accentuated at the left parietal position.

frame) at the left parietal (P₃) during functional matching than during the structural matching. Our data are too preliminary to permit a strong statement concerning the relationship of these differences to hemispheric specialization; it is conceivable that the changes at P₃ are related to task difficulty--recall that functional matching was performed more slowly and less accurately than structural matching. Figure 8 (bottom) shows that the func-

tional match power is smaller than structural match power at all electrode sites. Nonetheless, the differences are interesting and provide suggestive evidence of the efficacy of our tasks in differentially engaging the hemispheres.

Of central concern in the design of this experiment was the extent to which preparation to perform different analyses, presumed to engage the hemispheres differentially, would result in the formation of asymmetric CNVs prior to slide presentation.

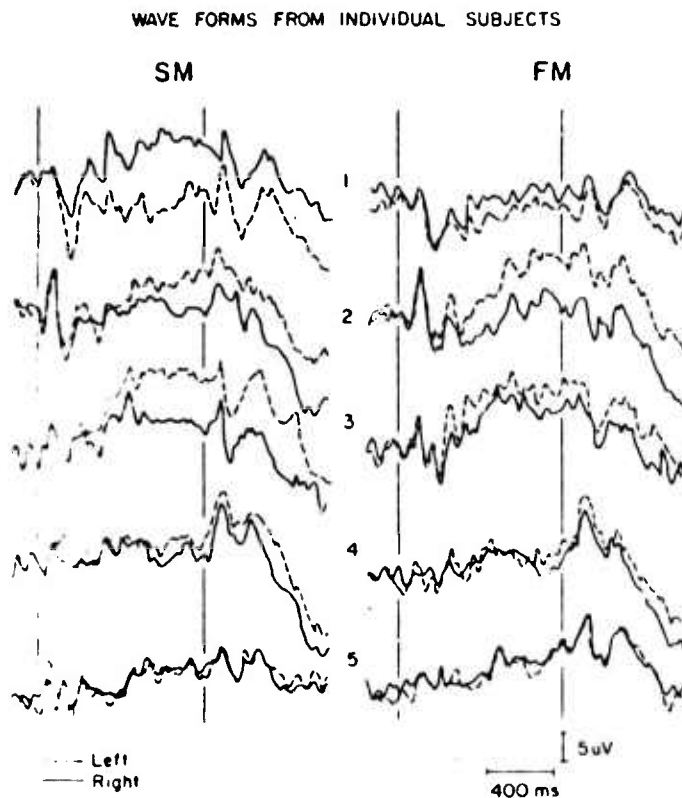
Grand averaged waveforms (Figure 9) for all experimental conditions reveal large asymmetries in the CNVs for all match conditions relative to the RT conditions. The most consistent asymmetries appear in the mixed conditions. Note that, when asymmetric, the left-hemisphere potential amplitudes always exceed the right-hemisphere potentials. In the mixed series, a prominent positive component appears 450 msec after the warning stimulus.



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Fig. 9. Grand-averaged waveforms for frontal, central, and parietal electrode positions for all experimental conditions for all trials in which the subject responded correctly. Right (solid line) and left (dashed line) lateral positions are superimposed. The vertical lines indicate the occurrences of the warning tone (S1) and slide (S2).

To illustrate the variability in the data, averaged waveforms from individual subjects for the mixed series are presented in Figure 10. For a more objective analysis, the waveforms from



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Fig. 10. LRP from five subjects for left (dashed line) and right (solid line) frontal electrode positions (superimposed) are shown for the mixed-match condition.

each subject, electrode, and condition were submitted as a data matrix to a Principal Components Analysis followed by Varimax rotation. Six orthogonal factors were extracted from the data, accounting for 78% of the experimental variance. A plot of the factor loadings, representing the degree of association of each time point with each factor, is presented in Figure 11. Such a plot identifies the temporal locus of activity for each of the factors. Factor scores, derived from these factor loadings, measure the degree to which each factor contributes to the waveforms for each condition and electrode placement. Thus, it is possible to assess the degree to which each factor is affected by the experimental conditions and to evaluate the relationships statistically. Space does not permit a full discussion of the behavior of each factor; attention will therefore be restricted to the two factors (1 and 2) clearly within the CNV region.

The time course of factor 1 is similar to that of a CNV, peak-

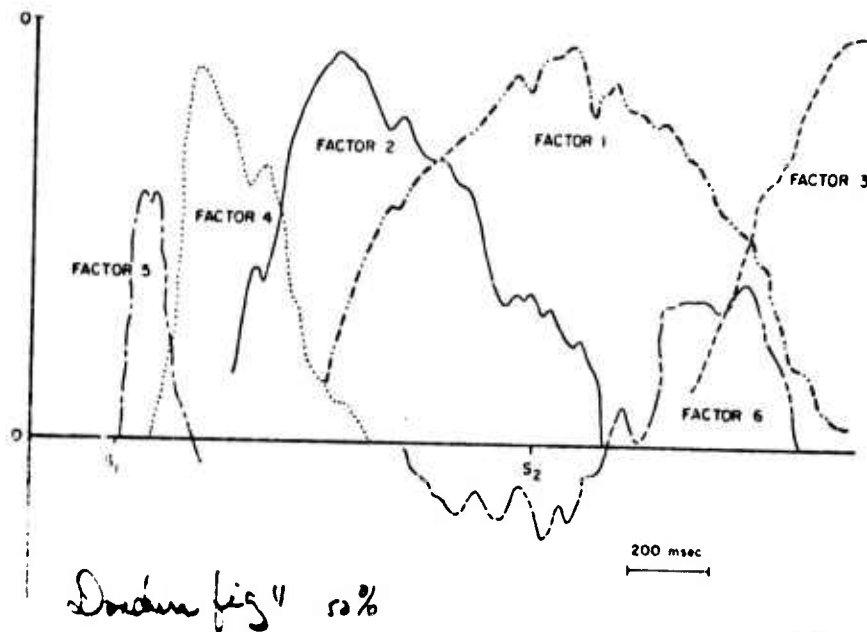


Fig. 11. Factor loadings for six orthogonal factors extracted by Principal Component Analysis and rotated by the Varimax procedure. The loadings represent the temporal locus of activity for each of the six factors.

ing just after the slide (S_2). The factor scores indicate that this factor is maximal at the central electrodes declining in amplitude in the frontal and parietal electrodes ($p < .001$, $F = 20.44$, $df = 7,29$). The decline is steeper toward the parietal than frontal sites. This scalp distribution has often been reported for the CNV. These scores also indicate that this component, which we identify with the CNV, is laterally asymmetric; it is more negative at the left hemisphere for all homologous pairs. This asymmetry appears to be affected by mode, appearing to be more marked for the mixed than the fixed series ($p < .025$, $F = 2.77$, $df = 7,28$). The three-way interaction, electrode position \times matching task \times mode ($p < .007$, $F = 3.51$, $df = 7,28$), indicates that this factor is largest for the two mixed conditions and indicates that the asymmetry is least pronounced in the functional fixed condition.

Factor 2 peaks approximately 475 msec after the warning tone (S_1). Its latency suggests that this factor may be the same as the early component of the CNV described by Loveless and Sanford (1974, 1975) and heretofore only seen with very long interstimulus intervals. Mode has a very pronounced effect upon the anterior-posterior distribution of this factor ($p < .001$, $F = 8.05$, $df = 7,28$). When S_1 conveys no information about the task to the subject (as in the fixed series), this factor is negative at all electrode sites, appearing largest frontally. When S_1 is task relevant (as in the mixed series), this component becomes positive in the parietal regions and marginally more negative frontally. The effect of matching tasks on this component is not

statistically significant ($p < .066$, $F = 2.18$, $df = 7, 28$) but nonetheless intriguing. At the frontal sites, this component appears to change its lateral distribution as a function of task; appearing larger over the left hemisphere for functional tasks and larger over the right hemisphere for structural matching.

The data just described demonstrate that CNVs of different amplitudes can be simultaneously recorded from homologous electrodes. The CNV is asymmetric when the matching mode varies randomly from trial to trial. The evidence also indicates that when the mode of matching is uniform over a block of trials (as in the fixed condition) the CNV is more symmetric. It seems then that the extent to which the asymmetry is observable may depend on the strategies the experimental situation permits the subject to adopt.

It is noteworthy that the direction of asymmetry is independent of the match required (structural versus functional). Clearly, the CNV does not reverse asymmetry in preparation for tasks that presumably engage one or the other hemispheres. A detailed replication of the experiment is now underway, using a larger sample and a richer set of control conditions. Although the new data seem to corroborate the data presented here, the nature of the observed asymmetry must be more fully elucidated in relation to the response requirements of the task.

Not directly related to the asymmetry question, yet a theoretically important aspect of these data, is the support they lend to the reports (Wæerts & Lang, 1973; Loveless & Sanford, 1974, 1975), that two distinct components may operate in the CNV interval. These components vary in scalp distribution and in their sensitivity to task demands.

SUMMARY

We have reviewed the evidence for the proposition that differences between the electrical activity recorded at homologous scalp locations over the left and right hemispheres can be used to index hemispheric utilization. There seems to be adequate support for the assertion that the ratio of EEG power over the hemispheres is sensitive to task variables. The direction of the difference is to some extent consistent with predictions derived from contemporary ideas about hemispheric specializations. Of the various ERP parameters studied, the ~~strongest~~ ^{most} results come from investigations of anticipatory potentials that appear to be asymmetric, again, in the predicted direction.

These trends are far from conclusive. Some methodological problems were reviewed. Attention should be paid to the independent validation of the behavioral effects of experimental instructions, to the greater sensitivity of within-group repeated-measures designs, to the choice of EEG parameters for study, and to the measurement and analysis of data.

We have presented data that demonstrate that (1) slow potentials preceding a voluntary self-paced motor response are largest over the hemisphere contralateral to the responding hand (at least in dextrals); (2) the preresponse asymmetry can coexist with cognitive anticipations which are symmetric; (3) the preresponse asymmetric readiness potentials appear to be followed by a prolonged potential shift with a polarity apparently inverse to that of the motor potential; (4) when the information-processing load is increased, some lateralization effects seem to occur in the CNV; and (5) both this CNV negativity and task-related shifts in power in the alpha band appear mostly as modulation of left-hemisphere activity rather than as reciprocal changes in hemispheric activities.

REFERENCES

- Adrian, E. D., & Matthews, B. H. C. The Berger rhythm: Potential changes from the occipital lobes in man. *Brain*, 1934, 57, 355-385.
- Aird, R. B., & Bowditch, S. Cortical localization by electroencephalography. *Journal of Neurosurgery*, 1946, 1, 245-261.
- Aird, R. B., & Zeale, D. S. The localizing value of asymmetrical electroencephalographic tracings obtained simultaneously by homologous recording. *Electroencephalography and Clinical Neurophysiology*, 1951, 3, 487-495.
- Andreassi, J. L., De Simone, J. J., Friend, M. A., & Grotta, P. A. Hemispheric amplitude asymmetries in the auditory evoked potential with monaural and binaural stimulation. *Physiological Psychology*, 1975, 3, 169-171.
- Andreassi, J. L., Okamura, H., & Stern, M. Hemispheric asymmetries in the visual cortical evoked potential as a function of stimulus location. *Psychophysiology*, 1975, 12, 541-546.
- Berger, H. Über das Elektrenkephalogramm des Menschen. Zweite Mitteilung. *Journal für Psychologie und Neurologie*, 1930, 40, 160-179.
- Broca, P. Remarques sur le siège de la faculté du langage articulé suivi d'une observation d'aphémie. *Bulletin Société Anatomie*, 1861, 6, 330-357.
- Brown, W. S., Marsh, J. T., & Smith, J. C. Contextual meaning effects on speech evoked potentials. *Behavioral Biology*, 1973, 9, 755-761.
- Bryden, M. P. Tachistoscopic recognition, handedness and cerebral dominance. *Neuropsychologia*, 1965, 3, 1-8.
- Buchsbaum, M., & Fedio, P. Visual information and evoked responses from the left and right hemisphere. *Electroencephalography and Clinical Neurophysiology*, 1969, 36, 266-272.
- Buchsbaum, M., & Fedio, P. Hemispheric differences in evoked potentials to verbal and nonverbal stimuli in the left and right visual fields. *Physiology and Behavior*, 1970, 5,

- 207-210.
- Buchwald, J. S., & Huang, C. M. Far-field acoustic response: Origins in the cat. *Science*, 1975, 189, 382-384.
- Butler, S. R., & Glass, A. Asymmetries in the electroencephalogram associated with cerebral dominance. *Electroencephalography and Clinical Neurophysiology*, 1974, 36, 481-491. (a)
- Butler, S. R., & Glass, A. Asymmetries in the CNV over left and right hemispheres while subjects await numeric information. *Biological Psychology*, 1974, 2, 1-16. (b)
- Butler, S. R., & Glass, A. EEG correlates of cerebral dominance. In *Advances in psychobiology*. New York: Wiley, 197 .
- Butler, R. A., Keidel, W. D., & Spreng, M. An investigation of the human cortical evoked potential under conditions of monaural and binaural stimulation. *Acta oto-laryngologica*, Stockholm, 1969, 68, 317-326.
- Callaway, E., & Harris, P. R. Coupling between cortical potentials from different areas. *Science*, 1974, 183, 873-875.
- Calmeil, R. L., & Cracco, R. Q. Comparison of somatosensory and somatomotor evoked responses to median nerve and digital nerve stimulation. *Electroencephalography and Clinical Neurophysiology*, 1971, 31, 547-562.
- Case, T. J., & Bucy, P. C. Localization of cerebral lesions by electroencephalography. *Journal of Neurophysiology*, 1938, 1, 245-261.
- Chapman, R. M. Evoked potentials of the brain related to thinking. In F. J. McGuigan & R. A. Schoonover (Eds.), *The psychophysiology of thinking: Studies of covert processes*. New York: Academic Press, 1973. Pp. 69-108.
- Cohen, J. Very slow brain potentials relating to expectancy: The CNV. In E. Donchin & D. B. Lindsley (Eds.), *Average evoked potentials, methods, results, and evaluation*. Washington, D.C.: NASA-191, U.S. Government Printing Office, 1969. Pp. 143-198.
- Cohen, J. CNV and visual recognition. In W. C. McCallum & J. R. Knott (Eds.), *Event related slow potentials of the brain*. New York: Elsevier, 1973. Pp. 201-204.
- Cohen, J., & Walter, W. G. The interaction of responses in the brain to semantic stimuli. *Psychophysiology*, 1966, 2, 187-196.
- Cohn, R. Differential cerebral processing of noise and verbal stimuli. *Science*, 1971, 172, 599-601.
- Cooper, R., Osselton, J. W., & Shaw, J. C. *EEG technology*. (2nd ed.) London: Butterworths, 1974.
- Cornil, L., & Gastaut, H. Étude électroencéphalographique de la dominance sensorielle d'une hémisphère cérébrale. *La Presse Médicale*, 1947, 37, 421-422.
- Culver, C. M., Tanley, J. C., & Eason, R. G. Evoked cortical potentials: Relation to hand dominance and eye dominance. *Perceptual and Motor Skills*, 1970, 30, 407-414.

Complete

- Deecke, L., Scheid, P., & Kornhuber, H. H. Distribution of readiness potential, pre-motion positivity, and motor potential of the human cerebral cortex preceding voluntary finger movements. *Experimental Brain Research*, 1969, 7, 158-168.
- Dimond, S. J., & Beaumont, J. G. (Eds.) *Hemisphere function in the human brain*. London: Paul Elek Ltd., 1974.
- Donchin, E. A multivariate approach to the analysis of average evoked potentials. *IEEE Transactions Biomedical Engineering*, 1966, BME-13, 131-139.
- Donchin, E. Data analysis techniques in evoked potential research. In E. Donchin & D. B. Lindsley (Eds.), *Average evoked potentials, methods, results, and evaluations*. Washington, D. C.: NASA-191, U.S. Government Printing Office, 1969. Pp. 199-236.
- Donchin, E. Methodological issues in CNV research. A review. In W. C. McCallum & J. R. Knott (Eds.), *Event related slow potentials of the brain*. New York: Elsevier, 1973. Pp. 1-17.
- Donchin, E. Brain electrical correlates of pattern recognition. In G. F. Inbar (Ed.), *Signal analysis and pattern recognition in biomedical engineering*. New York: John Wiley, 1975. Pp. 199-218.
- Donchin, E., Gerbrandt, L., Leifer, L., & Tucker, L. Is the contingent negative variation contingent on a motor response? *Psychophysiology*, 1972, 9, 178-188.
- Donchin, E., Kuzov, M., Kutas, M., Johnson, R. Jr., & Herning, R. I. Graded changes in evoked response (P300) amplitude as a function of cognitive activity. *Perception and Psychophysics*, 1973, 14, 319-324.
- Donchin, E., & Heffley, E. Minicomputers in the signal-averaging laboratory. *American Psychologist*, 1975, 30(3), 299-312.
- Donchin, E., Kutas, M., & Johnson, R. Jr. The CNV does not behave like a "motor" potential. *Electroencephalography and Clinical Neurophysiology*, 1974, 37, 434.
- Donchin, E., Kutas, M., & McCarthy, G. Comparison of the hemispheric asymmetries of the readiness potential and CNV. Paper read before the Psychonomic Society 15th Annual Meeting, Boston, 1974.
- Donchin, E., & Lindsley, D. G. (Eds.) *Average evoked potentials, methods, results, evaluations*. Washington, D.C.: NASA-191, U.S. Government Printing Office, 1969.
- Donchin, E., Tueting, P., Ritter, W., Kutas, M., & Heffley, E. On the independence of the CNV and P300 components of the human averaged evoked potential. *Electroencephalography and Clinical Neurophysiology*, 1975, 38, 449-461.
- Doyle, J. C., Ornstein, R., & Galin, D. Lateral specialization of cognitive mode: II. EEG frequency analysis. *Psychophysiology*, 1974, 11, 567-578.
- Dumas, R., & Morgan, A. EEG asymmetry as a function of occupation, task, and task difficulty. *Neuropsychologia*, 1975, 13, 219-228.

- Eason, R. G., Groves, P., White, C. T., & Oden, D. Evoked cortical potentials: Relation to visual field and handedness. *Science*, 1967, 156, 1643-1646.
- Fedio, P., & Buchsbaum, M. Unilateral temporal lobectomy and changes in evoked responses during recognition of verbal and nonverbal material in the left and right visual fields. *Neuropsychologia*, 1971, 9, 261-271.
- Friedman, D., Simson, R., Ritter, W., & Rapin, I. Cortical evoked potentials elicited by real speech words and human sounds. *Electroencephalography and Clinical Neurophysiology*, 1975, 38, 13-19.
- Galambos, R., Benson, P., Smith, T.S., Schulman-Galambos, C., & Osier, H. On hemispheric differences in evoked potentials to speech stimuli. *Electroencephalography and Clinical Neurophysiology*, 1975, 39, 279-283.
- Galin, D., & Ellis, R. R. Asymmetry in evoked potentials as an index of lateralized cognitive processes: Relation to EEG alpha asymmetry. *Psychophysiology*, 1975, 13, 45-50.
- Galin, D., & Ornstein, R. Lateral specialization of cognitive mode: An EEG study. *Psychophysiology*, 1972, 9, 412-418.
- Gazzaniga, M. S. *The bisected brain*. New York: Appleton, 1970.
- Gazzaniga, M. S., & Hillyard, S. A. Attention mechanisms following brain bisection. In S. Kornblum (Ed.), *Attention and performance IV*. New York: Academic Press, 1973. Pp. 221-238.
- Gerbrandt, L. K., Goff, W. R., & Smith, D. B. Distribution of the human average movement potential. *Electroencephalography and Clinical Neurophysiology*, 1973, 34, 461-474.
- Giannitrapani, D. Developing concepts of lateralization of cerebral functions. *Cortex*, 1967, 3, 353-370.
- Giannitrapani, D., & Darrow, C. W. Differences in EEG time relationships in right and left handed individuals. *Electroencephalography and Clinical Neurophysiology*, 1963, 15, 721P.
- Giannitrapani, D., Darrow, C. W., & Sorkin, A. Asleep and awake interhemispheric EEG phase relationships in left- and right-handed subjects. *American Psychologist*, 1964, 19, 480-481.
- Giannitrapani, D., Sorkin, A. I., & Ennenstein, J. Laterality preference of children and adults as related to interhemispheric EEG phase activity. *Journal of Neurological Science*, 1966, 9, 139-150.
- Gibbs, F. A., Lennox, W. G., & Gibbs, E. L. The electroencephalogram in diagnosis and in localization of epileptic seizures. *Archives of Neurology and Psychiatry*, 1936, 36, 1225-1235.
- Gilden, L., Vaughan, H. G., & Costa, L. D. Summated human EEG potentials associated with voluntary movement. *Electroencephalography and Clinical Neurophysiology*, 1966, 20, 433-438.
- Glanville, A. D., & Antonitis, J. J. The relationship between

- occipital alpha activity and laterality. *Journal of Experimental Psychology*, 1955, 49, 294-299.
- Goff, W. R., Matsumiya, Y., Allison, T., & Goff, G. D. Cross-modality comparisons of averaged evoked potentials. In E. Donchin & D. B. Lindsley (Eds.), *Average evoked potentials, methods, results, and evaluations*. Washington, D.C.: NASA-191, U.S. Government Printing Office, 1969. Pp. 143-198.
- Goff, W. R., Rosner, B. S., & Allison, T. Distribution of cerebral somatosensory evoked responses in normal man. *Electroencephalography and Clinical Neurophysiology*, 1962, 14, 697-713.
- Gott, P. S., & Boyarsky, L. L. The relation of cerebral dominance and handedness to visual evoked potentials. *Journal of Neurobiology*, 1972, 3, 65-77.
- Harmony, J., Ricardo, G. O., Fernandez, S., & Valdes, P. Symmetry of the visual evoked potential in normal subjects. *Electroencephalography and Clinical Neurophysiology*, 1973, 35, 237-240.
- Hécaen, H., & Ajuriaguerra, J. de. *Left-handedness: Manual superiority and cerebral dominance*. New York: Grune & Stratton, 1964.
- Hillyard, S. A. The CNV and human behavior: A review. In W. C. McCallum & J. R. Knott (Eds.), *Event related slow potentials of the brain*. New York: Elsevier, 1973. Pp. 162-172.
- Hoovey, Z. B., Meinemann, U., & Creutzfeldt, O. D. Inter-hemispheric "synchrony" of alpha waves. *Electroencephalography and Clinical Neurophysiology*, 1972, 32, 337-347.
- Irwin, D. A., Knott, J. R., McAdam, D. W., & Rebert, C. S. Motivational determinants of the "contingent negative variation". *Electroencephalography and Clinical Neurophysiology*, 1966, 21, 538-541.
- Jarvilehto, T., & Fruhstorfer, H. Differentiation between slow cortical potentials associated with motor and mental acts in man. *Experimental Brain Research*, 1970, 11, 309-317.
- Jewett, D., Romano, H. N., & Williston, J. S. Human auditory evoked responses: Possible brain stem components detected on the scalp. *Science*, 1970, 167, 1517-1518.
- Karlin, L. Cognition, preparation, and sensory-evoked potentials. *Psychological Bulletin*, 1970, 73, 122-136.
- Kimura, D. Cerebral dominance and the perception of verbal stimuli. *Canadian Journal of Psychology*, 1961, 15, 166-171.
- Kimura, D., & Durnford, M. Normal studies of hemisphere functions of the right hemisphere in vision. In S. J. Dimond & J. G. Beaumont (Eds.), *Hemisphere function in the human brain*. London: Paul Elek Ltd., 1974. Pp. 25-47.
- Kinsbourne, M. The control of attention by interaction between the cerebral hemispheres. In S. Kornblum (Ed.), *Attention and human performance IV*. New York: Academic Press, 1973. Pp. 239-256.

- Klinke, R., Fruhstorfer, H., & Finkenzeller, P. Evoked responses as a function of external and stored information. *Electroencephalography and Clinical Neurophysiology*, 1968, 25, 119-122.
- Kooi, K. A., Guvener, A. M., & Bagchi, B. K. Visual evoked responses in lesions of the optic pathways. *Electroencephalography and Clinical Neurophysiology*, 1965, 18, 524.
- Kornhuber, H. H., & Deecke, L. Hirnpotentialanderungen bei Willkurbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. *Pflugers Archiv fur die gesamte Physiologie des Menschen und der Tiere*, 1965, 204, 1-17.
- Kutas, M., & Donchin, E. Studies of squeezing: Handedness, responding hand, response force, and asymmetry of readiness potential. *Science*, 1974, 186, 545-548. (a)
- Kutas, M., & Donchin, E. Motor potentials force of response and handedness. In *Proceedings of the International Symposium on Cerebral Evoked Potentials in Man*, Brussels, 1975. (b)
- Kutas, M., McCarthy, G., & Donchin, E. Differences between sinistrals and dextrals in inferring a whole from its parts: A failure to replicate. *Neuropsychologia*, 1975, 13, 455-464.
- Lairy, G. C., Remond, A., Rieger, H., & Lesevre, N. The alpha average. III. Clinical application in children. *Electroencephalography and Clinical Neurophysiology*, 1969, 26, 453-467.
- Levy, J. Psychobiological implications of bilateral asymmetry. In S. J. Dimond & J. G. Beaumont (Eds.), *Hemispheric function in the human brain*. London: Paul Elek Ltd., 1974. Pp. 121-183.
- Lindsley, D. B. Bilateral differences in brain potentials from the two cerebral hemispheres in relation to laterality and stuttering. *Journal of Experimental Psychology*, 1940, 26, 211-225.
- Liske, E., Hughes, H. M., & Stowe, D. E. Cross-correlation of human alpha activity: Normative data. *Electroencephalography and Clinical Neurophysiology*, 1967, 22, 429-426.
- Livanov, M. N., Gavrilova, N. A., & Aslanov, A. S. Intercorrelations between different cortical regions of human brain during mental activity. *Neuropsychologia*, 1964, 2, 281-289.
- Livanov, M. N., Gavrilova, N. A., & Aslanov, A. S. Correlations of biopotentials in the frontal parts of the human brain. In K. H. Pribram & A. R. Luria (Eds.), *Psychophysiology of the frontal lobes*. New York: Academic Press, 1973. Pp. 91-107.
- Loveless, N. E., & Sanford, A. J. Slow potential correlates of preparatory sets. *Biological Psychology*, 1974, 1, 303-314.
- Loveless, N. E., & Sanford, A. J. The impact of warning signal intensity on reaction time and components of the contingent negative variation. *Biological Psychology*, 1975, 2, 217-226.

- Low, M. D., Borda, R. P., Frost Jr., J. D., & Kellaway, P. Surface-negative slow-potential shift associated with conditioning in man. *Neurology* (Minneapolis), 1966, 16, 771-782.
- Low, M. D., & McSherry, J. W. Further observations of psychological factors involved in CNV genesis. *Electroencephalography and Clinical Neurophysiology*, 1968, 35, 203-207.
- Low, M. D., Wada, J. A., & Fox, M. Hemispheric specialization for language production: Some electrophysiological evidence. *Proceedings of the International Symposium on Cerebral Evoked Potentials in Man*, Brussels, 1974.
- Low, M. D., Wada, J. A., & Fox, M. Electroencephalographic localization of the conative aspects of language production in the human brain. In W. C. McCallum & J. R. Knott (Eds.), *The responsive brain*. Bristol: John Wright, 1976. Pp. 165-168.
- MacKay, D. M. Evoked brain potentials as indicators of sensory information processing. *Neurosciences Research Program Bulletin*, 1969, 7(3), 181-276.
- Majkowski, J., Bochenek, Z., Bochenek, W., Knapik-Fijalkowska, D., & Kopec, J. Latency of averaged evoked potentials to contralateral and ipsilateral auditory stimulation in normal subjects. *Brain Research*, 1971, 25, 416-419.
- Manil, J., Desmedt, J. E., Debecker, J., & Chorazyna, H. Les potentiels cerebraux évoques par la stimulation de la main chez le nouveau-né normal. *Revue Neurologique*, 1967, 117, 52-61.
- Marsh, G. R., & Thompson, L. W. Effect of verbal and non-verbal psychological set on hemispheric asymmetries in the CNV. In W. C. McCallum & J. R. Knott (Eds.), *Event related slow potentials of the brain*. New York: Elsevier, 1973. Pp. 195-200.
- Matsumiya, Y., Tagliasco, V. L., Lombroso, C. T., & Goodglass, H. Auditory evoked response: Meaningfulness of stimuli and interhemispheric asymmetry. *Science*, 1972, 175, 790-792.
- McAdam, D. W., & Seales, D. M. Bereitschaftspotential enhancement with increased level of motivation. *Electroencephalography and Clinical Neurophysiology*, 1969, 27, 73-75.
- McAdam, D. W., & Whitaker, H. A. Language production: Electroencephalographic localization in the normal human brain. *Science*, 1971, 172, 499-502.
- McCallum, W. C., & Knott, J. R. (Eds.) *Event related slow potentials of the brain*. New York: Elsevier, 1973.
- McCallum, W. C., & Knott, J. R. (Eds.), *The responsive brain*. Bristol: John Wright, 1976.
- McCallum, W. C., & Papakostopoulos, D. Slow potential changes in human brainstem associated with preparation for decision or action. *Proceedings of the International Symposium on Cerebral Evoked Potentials in Man*, Brussels, 1974.
- McKee, G., Humphrey, B., & McAdam, D. W. Scaled lateralization of alpha activity during linguistic and musical tasks.

- Psychophysiology*, 1973, 10, 441-443.
- Milner, B. Hemispheric specialization: Scope and limits. In F. O. Schmitt & F. G. Worden (Eds.), *The neurosciences third study program*. Cambridge, Massachusetts: MIT Press, 1974. Pp. 75-89.
- Molfese, D. L., Freeman, R. B. Jr., & Palermo, D. S. The ontogeny of brain lateralization for speech and nonspeech stimuli. *Brain and Language*, 1975, 2, 356-368.
- Morgan, A. H., Macdonald, H., & Hilgard, E. R. EEG alpha: Lateral asymmetry related to task and hypnotizability. *Psychophysiology*, 1974, 11, 275-282.
- Morgan, A. H., McDonald, P. J., & Macdonald, H. Differences in bilateral alpha activity as a function of experimental task with a note on lateral eye movements and hypnotizability. *Neuropsychologia*, 1971, 9, 459-469.
- Morrell, L. K., & Huntington, D. A. Electrocortical cortical localization of language production. *Science*, 1971, 174, 1959-1960.
- Morrell, L. K., & Salamy, J. G. Hemispheric asymmetry of electrocortical response to speech stimuli. *Science*, 1971, 174, 164-166.
- Neville, H. Electrographic correlates of lateral asymmetry in the processing of verbal and nonverbal auditory stimuli. *Journal of Psycholinguistic Research*, 1974, 3, 151-163.
- Oldfield, R. C. The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, 1971, 9, 97-113.
- Otto, D. A., & Leifer, L. J. The effect of modifying response and performance on the CNV in humans. In W. C. McCallum & J. R. Knott (Eds.), *Event related slow potentials of the brain*. New York: Elsevier, 1973. Pp. 29-37.
- Peronnet, F., Michel, F., Echallier, J. F., & Girod, J. Coronal topography of human auditory evoked responses. *Electroencephalography and Clinical Neurophysiology*, 1974, 37, 225-230.
- Perry Jr., N. W., & Childers, D. G. *The human visual evoked response: Method and theory*. Springfield, Illinois: C. C. Thomas, 1969.
- Peters, J. F., & Mendel, M. I. Early components of the averaged electroencephalic response to monaural and binaural stimulation. *Audiology*, 1974, 13, 195-204.
- Poon, L. W., Thompson, L. W., Williams Jr., R. B., & Marsh, G. Changes of antero-posterior distribution of CNV and late positive component as a function of information processing demands. *Psychophysiology*, 1974, 11, 660-673.
- Price, L. L., Rosenblut, B., Goldstein, R., & Shepherd, D. C. The averaged evoked response to auditory stimulation. *Journal of Speech and Hearing Research*, 1966, 9, 361-370.
- Provine, K. A., & Cunliffe, P. The relationship between EEG activity and handedness. *Cortex*, 1972, 8, 136-146.
- Raney, E. T. Brain potentials and lateral dominance in identical

- twins. *Journal of Experimental Psychology*, 1939, 24, 21-39.
- Rebert, C. S., McAdam, P. W., Knott, J. R., & Irwin, D. A. Slow potential changes in human brain related to level of motivation. *Journal of Comparative and Physiological Psychology* 1967, 63, 20-23.
- Regan, D. *Evoked potentials in psychology, sensory physiology, and clinical medicine*. London: Chapman & Hall, 1972.
- Remond, A., Lesevre, N., Joseph, J. P., Rieger, H., & Lairy, G.C. The alpha average. I. Methodology and description. *Electroencephalography and Clinical Neurophysiology*, 1969, 26, 245-265.
- Rhodes, L. E., Dustman, R. E., & Beck, E. C. The visual evoked response: A comparison of bright and dull children. *Electroencephalography and Clinical Neurophysiology*, 1969, 27, 364-372.
- Rhodes, L. E., Obitz, F. W., & Creel, D. Effect of alcohol and task on hemispheric asymmetry of visually evoked potentials in man. *Electroencephalography and Clinical Neurophysiology*, 1975, 38, 661-668.
- Richlin, M., Weisinger, M., Weinstein, S., Giannini, M., & Morganstern, M. Interhemispheric asymmetries of evoked cortical responses in retarded and normal children. *Cortex*, 1971, 7, 98-104.
- Rohrbaugh, J., Donchin, E., & Ericksen, C. W. Decision making and the P300 component of the cortical evoked response. *Perception and Psychophysics*, 1974, 15, 368-374.
- Ruchkin, D. S., Villegas, J., & John, E. R. An analysis of averaged evoked potentials making use of least mean squares techniques. *Annals of the New York Academy of Sciences*, 1964, 115, 799-826.
- Ruhm, H. B. Lateral specificity of acoustically evoked EEG responses. I. Non-verbal, non-meaningful stimuli. *Journal of Auditory Research*, 1971, 11, 1-8.
- Satz, P., Achenbach, K., & Fennell, E. Correlations between assessed manual laterality and predicted speech laterality in a normal population. *Neuropsychologia*, 1967, 5, 295-310.
- Schenkenberg, T., & Dustman, R. E. Visual, auditory, and somatosensory evoked response changes related to age, hemisphere and sex. *Proceedings of the 78th Annual Convention of the American Psychological Association*, 1970, 183-184.
- Shagass, C. *Evoked brain potentials in psychiatry*. New York: Plenum Press, 1972.
- Shelburne Jr., S. A. Visual evoked responses to word and non-sense syllable stimuli. *Electroencephalography and Clinical Neurophysiology*, 1972, 32, 7-25.
- Shelburne Jr., S. A. Visual evoked responses to language stimuli in normal children. *Electroencephalography and Clinical Neurophysiology*, 1973, 135-143.
- Smith, A. Dominant and nondominant hemispherectomy. In W. L. Smith (Ed.), *Drugs, development and cerebral function*. Springfield, Illinois: C. C. Thomas, 1972.

- Sperry, R. W. Lateral specialization in the surgically separated hemispheres. In F. O. Schmitt & F. G. Worden (Eds.), *The neurosciences third study program*. Cambridge, Massachusetts: MIT Press, 1974. Pp. 5-19.
- Dubirana, A. Handedness and cerebral dominance. In P. J. Vinken & G. W. Bruyn (Eds.), *Handbook of Clinical neurology*, Vol. 4. Amsterdam: North-Holland Pub., 1969. Pp. 248-272.
- Sutton, S., Braren, N., Zubin, J., & John, E. R. Evoked-potential correlates of stimulus uncertainty. *Science*, 1965, 155, 1187-1188.
- Sutton, S., Tueting, P., Zubin, J., & John, E. R. Information delivery and the sensory evoked potential. *Science*, 1967, 155, 1436-1439.
- Syndulko, K. Relationships between motor potentials and CNV. *Electroencephalography and Clinical Neurophysiology*, 1969, 27, 706.
- Syndulko, K. Cortical slow potential shifts in humans during sensory and motor tasks. Unpublished doctoral dissertation, Univ. of California, Los Angeles, 1972.
- Teyler, T., Harrison, T., Roemer, R., & Thompson, R. Human scalp recorded evoked potential correlates of linguistic stimuli. *Journal of the Psychonomic Society Bulletin*, 1973, 1, 333-334.
- Thompson, R. F., & Patterson, M. M. (Eds.) *Bioelectric recording techniques. Part B: Electroencephalography and human brain potentials*. New York: Academic Press, 1974.
- Travis, L. E., & Knott, J. R. Bilaterally recorded brain potentials from normal speakers and stutterers. *Journal of Speech Disorders*, 1937, 2, 239-241.
- Tueting, P., & Sutton, S. The relationship between pre-stimulus negative shifts and post-stimulus components of the averaged evoked potential. In S. Kornblum (Ed.), *Attention and performance IV*. New York: Academic Press, 1973. Pp. 185-207.
- Vaughan, H. G. The relationship of brain activity to scalp recording of event-related potentials. In E. Donchin & D. B. Lindsley (Eds.), *Average evoked potentials, methods, results, and evaluation*. Washington, D.C.: NASA-191, U.S. Government Printing Office, 1969. Pp. 143-198.
- Vaughan, H. G., Jr. The analysis of scalp-recorded brain potentials. In R. F. Thompson & M. M. Patterson (Eds.), *Bio-electrical recording techniques. Part B: Electroencephalography and human brain potentials*. New York: Academic Press, 1974. Pp. 157-207.
- Vaughan, H. G., Costa, L. D., & Ritter, W. Topography of the human motor potential. *Electroencephalography and Clinical Neurophysiology*, 1968, 25, 1-10.
- Vaughan, H. G., Katzman, R., & Taylor, J. Alterations of visual evoked response in the presence of homonymous visual defects. *Electroencephalography and Clinical Neurophysiology*, 1963, 15, 737-746.

- Vaughan, H. G., & Ritter, W. The sources of auditory evoked responses recorded from the human scalp. *Electroencephalography and Clinical Neurophysiology*, 1970, 28, 360-367.
- Vella, E. J., Butler, S. R., & Glass, A. Electrical correlates of right hemisphere function. *Nature*, 1972, 236, 125-126.
- Walter, W. G. The location of cerebral tumors by electroencephalography. *Lancet*, 1936, 2, 305-312.
- Walter, W. G., Cooper, R., Aldridge, V. J., McCallum, W. C., & Winter, A. L. Contingent negative variation: An electric sign of sensorimotor association and expectancy in the human brain. *Nature*, 1964, 203, 380-384.
- Walter, D. O., Rhodes, J. M., Brown, D., & Adey, W. R. Comprehensive spectral analysis of human EEG generators in posterior cerebral regions. *Electroencephalography and Clinical Neurophysiology*, 1966, 20, 224-237.
- Weerts, T. C., & Lang, P. J. The effects of eye fixation and stimulus and response location on the contingent negative variation (CNV). *Biological Psychology*, 1973, 1, 1-19.
- Wilke, J. T., & Lansing, R. W. Variations in the motor potential with force exerted during voluntary arm movements in man. *Electroencephalography and Clinical Neurophysiology*, 1973, 65, 259-265.
- Wood, C. C., Goff, W. R., & Day, R. S. Auditory evoked potentials during speech perception. *Science*, 1971, 173, 1248-1251.
- Zimmermann, G. N., & Knott, J. R. Slow potentials of the brain related to speech processing in normal speakers and stutterers. *Electroencephalography and Clinical Neurophysiology*, 1974, 37, 599-607.
- Zurif, E. B., & Bryden, M. P. Familial handedness in left-right difference in auditory and visual perception. *Neuropsychologia*, 1969, 7, 179-187.

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ON THE INFLUENCE OF TASK RELEVANCE AND STIMULUS PROBABILITY ON EVENT-RELATED-POTENTIAL COMPONENTS *

KENNETH C. SQUIRES, EMANUEL DONCHIN, RONALD I. HERNING[†] and GREGORY MCCARTHY
 Cognitive Psychophysiology Laboratory,
 Department of Psychology, University of Illinois, Champaign, Ill. 61820 (U.S.A.)

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The concept of "components" has played a central role in the study of average event-related potentials (ERPs). Most investigators report, and discuss, the experimental variables in terms of their effects on one, or on several, components. The ERP is thus viewed as a sequence of serially activated processes manifested on the scalp as distinct positive-negative potential fluctuations. It has been customary to identify the components by the presence or absence of prominent peaks at particular latencies. Numerous investigators have reported striking effects on a component labeled P300 (or P3) of independent variables which manipulate the psychological context in which the eliciting stimulus has been presented (cf. Price and Smith 1974). With few exceptions (Donchin et al. 1973, 1975) these results have been reported in terms of the base-to-peak amplitude of a peak in the waveform with a latency of 250-450 msec.

N. Squires et al. (1975) presented data suggesting that several additional components can be observed within an interval ranging from 100 to 600 msec after the eliciting

event which are affected by those variables known to affect P300. Their interest was centered mostly on a positive peak with a latency of about 270 msec which they labeled P3a, whose appearance, unlike P300, did not depend on stimulus relevance. They also mention a N200, which was probably related to similar components at about this latency which have been reported by Ford et al. (1973), Picton et al. (1974), Simson et al. (1976) and Ruchkin and Sutton (in press). Finally they report that a "slow wave" follows P300 which was, like P300, sensitive to stimulus relevance, but which could not be easily dissociated from the P300.

The problem, of course, is that when two components summate they may not be separable on the basis of variations in peak amplitude alone. It is also rather difficult to determine whether an experimental variable affects a given component directly or indirectly (through an effect on another, overlapping, component). It is apparent, then, that as the process underlying the generation of the ERP are resolved with ever-finer detail, exclusive reliance on the visual identification of components alone becomes increasingly inadequate (Donchin 1966, 1969).

As N. Squires et al. (1975) state, they have found it difficult to dissociate the "slow wave" from P300. Neither have they clarified the relationship between N200 (N2 in their terminology) and the P3a component. Yet, the dissociation of these components is of considerable significance in view of Näätänen's

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[†] Present address: The Langley Porter Research Institute, University of California Medical School, San Francisco, Calif.

Present address: Department of Medicine,
 University of California at San Diego, 101 City
 Drive South, San Diego, California 92161.

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(1975) "three component hypothesis of the EP". In a very detailed and critical analysis of the P300 literature Näätänen questions the distinctness of P300 as an endogenous component of the evoked potential. In his view, "... many components claimed to be P3 or P300 and many reported enhancements of this component might in fact signify 'only' a non-specific change of state of the organism (occurring most often after the relevant stimulus) or to be of artifactual origin" (Näätänen 1975, p. 280).

To account for the data which appear to contradict his view Näätänen postulates "a temporally overlapping longer-duration positive process which might start already at 50–100 msec post stimulus, peak at 200–500 msec post stimulus and last up to 1 second ... This component overlaps two negative peaks — N1 and N2 — which together with this slow positive component determine the waveform of the ERP".

Näätänen's view is persuasively argued, but it lacks direct evidence. The slow positivity he posits might be closely related to the "slow wave" described by N. Squires et al. (1975). It thus becomes important to determine the relationship of the P300 and the slow wave. Are these two distinct components, or are they as Näätänen seems to propose, two aspects of the same component. Similar reasoning applies to the problem of the relationship of P3a and the N200, which according to Näätänen would also interact.

It is of course difficult to dissociate such overlapping components. The problem, however, is somewhat analogous to the problem of the relationship between the contingent negative variation (CNV) and P300. This problem has been successfully tackled by Donchin et al. (1975) using the Principal Component technique for dissecting apart evoked response components. We decided therefore to apply the same technique to data collected in the manner described by N. Squires et al. (1975). Thus in this paper we report a replication of the Squires et al. study, the intent of which was to examine in more

detail the ERP components which occur in the time range of 150–600 msec after the stimulus *.

Methods

Experiment I

Subjects. Nine normal young adults, including three experimenters, served as subjects. Two of the non-experimenter subjects had served in previous evoked potential experiments but they, along with the four naive subjects, were not familiar with the purpose of the experiment.

Stimuli. Tone bursts were delivered binaurally through TDH-39 earphones at the rate of one every 1.3 sec. Tone frequency was 100 c/sec and each tone was of a total duration of 60 msec (10 msec rise–fall time) gated in a random phase. Two signal levels were used, the "loud" stimulus was 80 dB SPL and the "soft" stimulus was 60 dB SPL. Stimuli were presented against a continuous background of wide-band noise at 50 dB SPL.

Recording system. The EEG was recorded from 9 electrode sites (P₃, C₃, F₃, P_z, C_z, F_z, P₄, C₄ and F₄ according to the 10–20 system) referred to linked mastoids. The ground electrode was on the right wrist. For scalp recording Burden Ag–AgCl electrodes were affixed with collodion. Beckman biopotential electrodes were affixed on the mastoids with adhesive collars. In addition, Beckman electrodes were placed above and below the right eye to record the EOG and blink potentials in parallel with the scalp recordings.

Electrical potentials were amplified with Grass 7P122 amplifiers (time constant 0.8 sec and upper half amplitude frequency 60 c/sec).

* We feel that there are all too few replications of experiments in evoked potential research. In our view progress in our understanding of the ERP depends on the accumulation of a body of well substantiated, replicated, data, and if a replication allows a more detailed look at the components, so much the better.

The EEG was sampled for 768 msec beginning 100 msec prior to stimulus onset at a rate of 333 samples/sec (1 sample every 3 msec).

Data collection. The experiment was controlled by a PDP11/40 computer which was also responsible for data acquisition (Donchin and Hefley 1975). Digitized single-trial data, as well as ERPs averaged on-line for each block of trials, were stored on digital magnetic tape for later analysis. Eye movement and blink artifacts were removed off-line, either by eliminating the block-average ERP in which substantial EOG activity appeared, or by recomputing the ERP using the single-trial data and eliminating trials with EOG artifacts. Data analyses, using the SOUPAC statistical package (Dickman 1972), were performed either at the Computer Services Office of the University of Illinois or the Campus Computing Network at UCLA, using the ARPANET for communication. Most analyses were duplicated with the BMD-P package (Dixon 1975).

Procedure. The subject sat in a reclining chair in an unshielded experimental room. Prior to each block of 200 trials the subject was instructed, via an intercom, either to listen to the train of tones and count the number of loud tones, to be reported at the end of the block, or to ignore the tones and concentrate on another task. In the latter condition, the subjects searched for words in a matrix of letters, except for the three experimenters, who read a book. In the word-game task a bonus was paid according to the number of words correctly identified. Data obtained in this condition are labeled "ignore" in all figures and tables.

Within each block of trials the probability that the loud stimulus would occur on any trial was either 0.10 or 0.90 (the soft stimulus was presented at the complementary probability). Prior to each block the subject was informed of the probability of each stimulus.

The experimental design was a repeated-measurement, 4-way factorial design. The four main factors were stimulus intensity (loud vs. soft), stimulus probability (rare vs. frequent), task (count vs. ignore), and elec-

trode location (with subject variance appearing in the error term, cf. Keppel 1974). Each combination of stimulus probability and task requirement was repeated 3 times within a single 2 h experimental session (a total of 600 trials per condition). Thus on 60 trials the rare stimulus was presented and on 540 trials the frequent stimulus was presented. Note that while the design calls for 8 "cells" (excluding the electrode factor), only 4 series were used, each series yielding data for two of the cells, one set of waveforms for loud stimulus and one for soft. For each subject, the second series balanced the first series and the third was either the same as the first or quasi-randomized to control for order effects. The initial series differed over subjects.

Experiment II

The experiment was repeated with nine subjects, three of whom participated in Experiment I. Of the six new subjects, two had participated in previous evoked potential experiments. All experimental procedures were identical to those used in Experiment I, except that experimental series were added in which the subject was instructed to count the rare-soft stimuli. There were thus 6, rather than 4, trial series for each subject. Each condition was presented twice for a total of 400 stimulus presentations. In the "ignore" condition all subjects performed the word-game task.

Results

A review of ERP waveforms

The ERP waveforms obtained from the three midline electrode sites (P_z , C_z and F_z) in all four experimental conditions in Experiment I are shown for one subject in Fig. 1.

The ERPs elicited by frequent stimuli ($P = 0.9$) in all experimental conditions were characterized by the N100 and P160 peaks of the auditory evoked potential (Davis 1965).

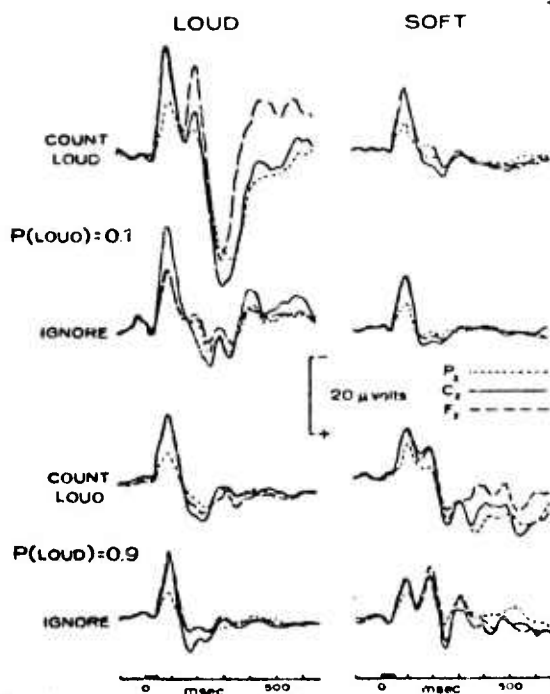


Fig. 1. ERP waveforms for one subject for the eight conditions in Experiment I, at the three mid-line electrode sites (P_z , C_z , P_z). The loud stimulus ERP waveforms are on the left and those for the soft stimulus are on the right. In the upper half of the figure are the waveforms from the conditions where the probability of the loud stimulus was 0.1, and the count loud condition is shown above the ignore condition. The corresponding waveforms when the probability of the loud stimulus was 0.9 are shown in the bottom half of the figure. The total waveform epoch is 768 msec and stimulus occurrence is indicated by the black bar on the time scale. Negativity at the active electrode is shown upwards in all figures.

No additional peaks were prominent in those waveforms.

Rare stimuli ($P = 0.1$) elicited ERPs with complex waveforms, the exact shape of which depended upon the task relevance of the tones. For task-relevant, rare stimuli a large positive peak with a mean latency of 358 msec (P350) appeared in the waveform. Also clear in those waveforms were a "slow wave" (SW), predominant over the last 200 msec of the epoch, and a negative peak preceding

P350 with a mean latency of 213 msec (N210). On the leading slope of P350 another positive peak was discernible, often only as an inflection, at a mean latency of 282 msec.

When the tones were rare but irrelevant a quite different picture emerged. The P350 peak was much reduced in amplitude relative to when the stimuli were task-relevant and the SW was absent. The N210 peak (mean latency 215 msec) remained prominent and was often followed by a positive peak (P270).

The data from four subjects in Experiment I who exhibited the major variants of the ERP waveform are shown in Fig. 2 to illustrate the range of intersubject variability. Here, the rare-stimulus ERPs recorded at C_z in two experimental conditions are superimposed upon the ERPs elicited by physically identical stim-

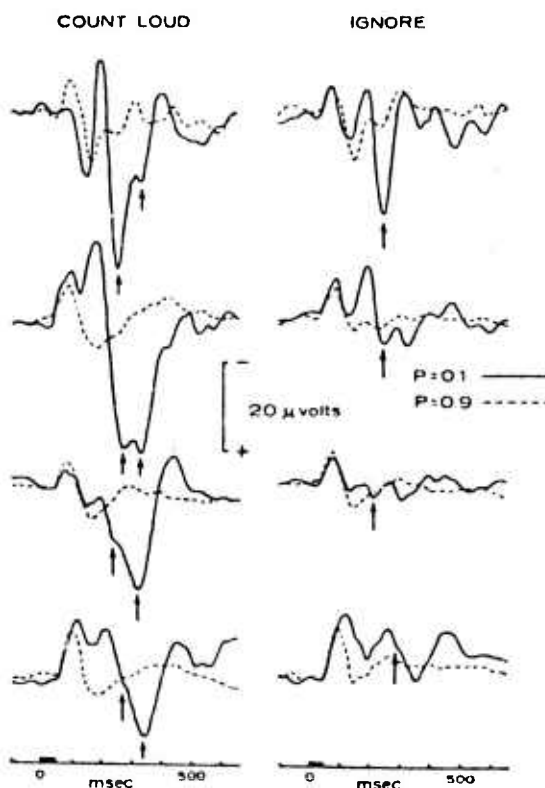


Fig. 2. Superimposed ERP waveforms for rare and frequent stimuli in the attend and ignore conditions for four subjects.

uli in the same condition when these stimuli were frequent. While the peaks enumerated above are generally identifiable, the relative contributions of each peak to the overall waveform varied considerably across subjects.

It is important to emphasize that the data acquired in the present experiments replicated in all important aspects the data described by N. Squires et al. (1975). The range of inter-subject waveform variability observed in both laboratories is similar, as comparisons of the ERP waveforms in Fig. 1 and 2 of both reports would reveal. While the mid-latency negative peak (N210) and the bifurcated nature of the positive peak, with an inflection or an additional peak appearing at the arrows are easily observed, it is not clear how the relative amplitude of each of the peaks should be asayed.

Within any of the waveforms associated with rare stimuli, several components are apparently active within the first 600 msec following the stimuli (those represented by N100, P160, N210 and P270 peaks), and when the stimuli are task-relevant two more components (P350 and SW) may also be present. Depending upon the temporal characteristics of the components, any variations in the form of one component due to experimental manipulation may result in the apparent variations in one or more components that overlap it in time. This, in fact, is Näätänen's claim. He contends that the enhanced P300 is a manifestation of slow, long-term positivity. In the context of these data his position seems to imply an identity of the slow wave and P300.

Principal Components analysis

Introductory remarks

In order to disentangle the effects of multiple components so that the extent to which components are distinct in their response to the experimental variables, the ERP data were subjected to a Principal Components analysis followed by an analysis of variance (Donchin 1966, 1969; Donchin et al. 1975). It is perhaps necessary to dwell here on the essential

similarity between Principal Components analysis and the base-to-peak procedure which is more often used in analyzing ERP data. Both procedures transform each ERP, which generally consists of 50–500 successive measures of voltage, into a set of 5–6 measures. These measures are always "linear combinations" of the ERP data. A linear combination of a set of voltage values X_i (with i ranging from 1 to N , N being the number of digitized values in the ERP) is obtained by multiplying each X_i by a coefficient a_i and summing over all the i 's. Clearly, for any set of X_i any number of linear combinations can be formed by selecting many different sets of coefficients (a_i). Measuring the base-to-peak amplitude at point k of a component of the ERP is equivalent to setting the value of a_i for some $i = k$ to 1.0 and zeroing all the other a_i values. The linear combination thus formed is then taken to represent an ERP component. The selection of the i at which $a_i = 1.0$ is made by identifying a latency range within which the investigator believes a component to exist and identifying the value of i within that range for which X_i is maximal. The latency ranges are chosen because the ERP waveform changes within them in a consistent manner over the entire set of ERPs.

Principal Components analysis defines components similarly. It identifies the latency ranges over which distinct, orthogonal, sources of experimental variance can be identified. For each such source of variance it provides a set of a_i 's such that the linear combinations formed will be orthogonal. These linear combinations, known as factor scores, are logically equivalent to the base-to-peak measures. They have, however, several advantages: (a) Being orthogonal, the factor scores for each component can be subjected to univariate analysis of variance (ANOVA). The commonly encountered computations of separate ANOVAs for each peak measure are of doubtful validity due to the possible correlation between measures in different parts of the waveform. (b) The process of identifying the components and computing the linear combina-

tions is objective and is rigorously defined. Any two investigators, using the same data base, will obtain the same set of factor scores. The results will depend, of course, on the experimental design. Analytical techniques can only reveal the effects of the experimental variables on the data. In this way the experimenter always plays a role, but this feature is inherent in all data analysis techniques. (c) The entire data set contributes to the factor scores, rather than the values at a few selected time points. This increases the sensitivity of the experimental procedures as it reduces the effect of noise and sampling fluctuations on the measurements. (d) In the appropriately equipped laboratory the conduct of a Principal Components analysis facilitates the analysis of many hundreds of ERPs, collected in experiments of considerable complexity. All that is required is that the ERPs be available in computer-compatible form.

The use of Principal Components is not a universal panacea for ERP research. No technique is. We find it very useful whenever the experimental manipulations are likely to affect the relative amplitudes of overlapping ERP components with minimal effects on latency. The technique is, however, quite weak when experimental manipulations affect the latencies of ERP peaks. It may also be inadequate if there are strong non-linear interactions amongst the underlying components. As it is usually applied, the technique is also blind to any feature of the ERP waveform that is not influenced by the experimental manipulations. In previous studies we extracted the Principal Components from the correlation matrix of the data. This procedure subtracts the mean and scales the data at each time point by its variance. Since the Principal Components are components of the experimental variance no components will be extracted corresponding to peaks which remain unchanged across all experimental conditions (such as P160 in these data). An alternative method, which was used here, is to analyze the cross-product matrix of the data. This method retains information about relative

variations in amplitude, which are of prime interest here, and relates all variability to a pre-stimulus baseline. As such, the resulting Principal Components are conceptually similar to ERP components which are positive and negative voltage variations rather than variations about some mean waveform which may depend strongly upon the mix of experimental conditions.

Results

The data obtained in the two experiments were analyzed separately. The data base for each analysis was a set of 648 ERP waveforms (2 stimuli \times 2 stimulus probabilities \times 2 task conditions \times 9 electrode sites \times 9 subjects), each with 64 time points (12 msec/point). The waveforms for the third, "count sort", condition of Experiment II were omitted from the primary analysis reported here to balance completely the design (equal numbers of ERPs from the count and ignore conditions).

Table I presents the percent of the total variance accounted for by each of the first 20 factors extracted from the data from each experiment. In both cases, most of the variance was accounted for by the first 6 factors (93% for Experiment I and 91% for Experiment II). Much evidence is available showing that an ERP data matrix can be adequately represented by 6 variables (see Donchin 1966, 1969; Donchin et al. 1970; Donchin and Haming 1975). Only the first 6 factors were therefore used in all further analyses. These 6 factors were then subjected to a Varimax rotation. A Varimax rotation, while arbitrary, is intuitively appealing; it retains an orthogonal factor space while maximizing the association between each factor and a few time points, minimizing the correlation at all other points for each factor. (In fact, an evoked potential data matrix fulfills many of the preconditions enumerated by Harshman (1970) for the use of the Varimax procedure.) The correlation between each component and a time point is called a factor "loading" and in our procedure it was the factor loadings which were Varimax-

TABLE I

Percent variance accounted for by each of the first 20 factors.

Factor	Experiment I		Experiment II	
	Percent variance	Cumulative percent	Percent variance	Cumulative percent
1	54.6	54.6	47.4	47.4
2	13.1	67.7	19.7	67.1
3	12.4	80.1	12.3	79.4
4	6.0	86.1	5.6	85.0
5	4.2	90.3	3.6	88.6
6	2.6	92.9	2.5	91.1
7	1.3	94.2	2.3	93.4
8	0.9	95.1	0.9	94.3
9	0.8	95.9	0.8	95.1
10	0.5	96.4	0.7	95.8
11	0.5	96.9	0.6	96.4
12	0.5	97.4	0.5	96.9
13	0.3	97.7	0.5	97.4
14	0.2	97.9	0.3	97.7
15	0.2	98.1	0.3	98.0
16	0.2	98.3	0.2	98.2
17	0.2	98.5	0.2	98.4
18	0.2	98.7	0.2	98.6
19	0.1	98.8	0.1	98.7
20	0.1	98.9	0.1	98.8

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Experiment I ———
Experiment II - - - - -

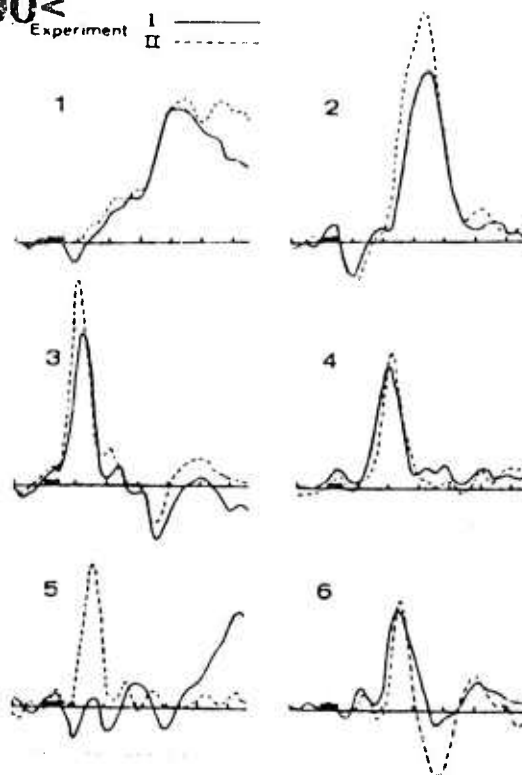


Fig. 3. Factor loadings for the 6 factors extracted by the Principal Components analyses of Experiment I (solid lines) and Experiment II (dashed lines). As in Fig. 1, the time scale is 768 msec.

rotated. The factor loadings after the Varimax rotation are plotted in Fig. 3 for Experiment I against the corresponding time points (solid lines). The factor loadings serve to indicate the degree of association between a factor and each of the 64 time points. For instance, Factor 1 is most highly correlated with time points in the latter portion of the epoch. It is over that same portion of the ERP that the SW can be identified; consequently we identify Factor 1 with the SW. Similarly, Factor 2 has a peak loading at about the latency of P350. Factor 3 is heavily loaded at the latency of N100 and has a reciprocal loading at the latency of P350. Factor 4 peaks at 200 msec, suggesting an equivalence to the N210 peak of the ERP. Factor 5 has no prominent peaks. Factor 6 loads most heavily at 250 msec. For more detail concerning the Princi-

pal Components and factor loadings, see Donchin et al. (1975).

Also shown in Fig. 3 (dashed lines) are the Varimax-rotated loading functions from Experiment II. Note that each loading function from Experiment II, except for Factor 5, has a time course similar to that of the analogous factor from Experiment I. It is of some interest that the ordering of factors according to the percent variance accounted for was the same for both experiments. While separation of components of the ERP waveform through the use of Principal Components has been demonstrated previously (Donchin et al. 1975; Kutas and Donchin, *in press*), these data are remarkable in demonstrating a virtually iden-

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tical factor structure in two different samples*.

The factor loadings serve merely to indicate the segments of the epoch over which the 6 factors are maximally active. These data suggest an identification between, at least some, factors and classical ERP components, but such interpretations are greatly bolstered through a study of the behavior of the factors as a function of the experimental variables. The factor scores were therefore evaluated for each of the 648 waveforms for each of the factors. In Fig. 4 the mean factor scores for all factors except Factor 5 are presented for the three midline electrodes for all experimental conditions. Since the results of the two experiments were essentially identical the scores for all subjects in both experiments were averaged in Fig. 4. These data summarize the trends of the relationships between the factor scores, amplitudes, and the experimental variables. The reliability of these trends was evaluated by performing independent ANOVAs of the factor scores of each of the factors. The results of these ANOVAs are shown in Table II.

An examination of the ANOVA results reveals that the SW factor (Factor 1) was significantly affected by the signal intensity, by task requirement (count vs. ignore) and by the electrode site. No main effect of signal probability was apparent, due to the strong interaction between electrode site and signal probability. The P350 factor (Factor 2) was modulated by the same variables as the SW factor. In addition, the effect of signal probability on this factor was statistically significant. The N100 factor (Factor 3) was influenced by signal intensity in Experiment I but not in Experiment II. It varied with electrode site but

* It should be noted that similar component structures have been obtained in our laboratory in other experiments in which the experimental procedures were markedly different than the ones used here. For example, both McCarthy and Donchin (1975) and Duncan-Johnson and Donchin (in preparation) observed factors which are clearly analogous to Factors 1 and 2 we report here.

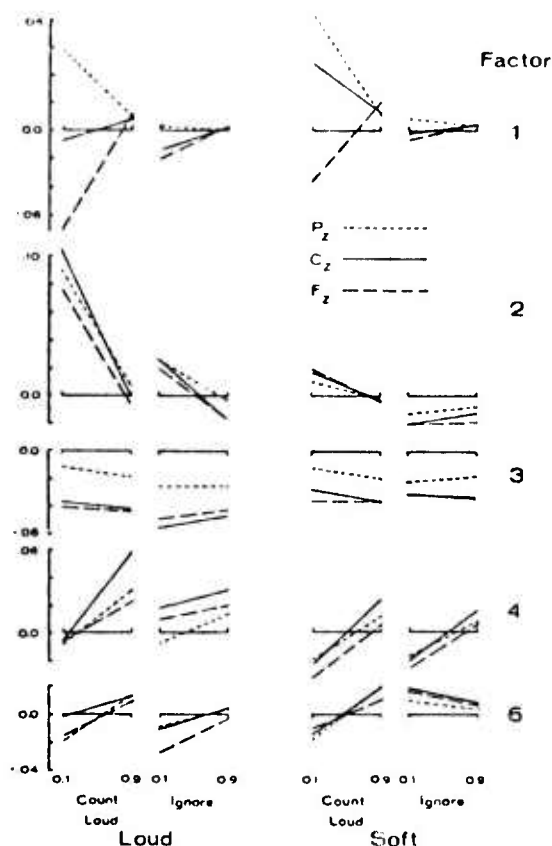


Fig. 4. Mean factor scores for all factors except Factor 5 from P_z , C_z and F_z in the eight experimental conditions.

was unrelated to signal probability or to the subject's task. The N100 factor (Factor 4) was affected by signal probability and electrode site but unlike the P350 and SW it was independent of task requirement.

These general statements about the effects of experimental variables on the various components are given substance by the plots of the factor scores in Fig. 4.

The slow wave shows a dramatic interaction between electrode site and signal probability when tones are task-relevant (Fig. 4). The factor scores are large and of opposite sign at F_z and P_z for relevant stimuli. The scores are near zero for all frequent stimuli and for both rare and frequent tones when the tones are ignored.

TABLE II

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Summary of analyses of variance. The top entry for each source and factor is the F-value from Experiment I and the bottom entry is the F-value from Experiment II.

Source/Factor	df	1	2	3	4	5	6
A(Signal)	1,8	6.26 * 17.34 *	38.82 * 37.07 *	7.31 * 3.13	4.76 * 12.37 *	0.01 0.21	0.38 4.62
B(Probability)	1,8	0.43 0.67	72.72 * 17.27 *	0.01 0.20	8.77 * 9.12 *	0.01 6.13 *	9.64 * 0.50
C(Task)	1,8	13.51 * 6.12 *	7.87 * 38.24 *	2.79 0.71	0.02 0.09	1.00 0.58	0.13 1.07
D(Electrode)	8,64	28.66 * 10.53 *	2.77 * 5.12 *	20.19 * 6.32 *	2.42 * 5.49 *	0.85 1.06	1.12 1.46
A × B	1,8	2.81 13.65 *	37.75 * 45.54 *	3.17 0.26	0.03 3.46	0.17 4.19	0.18 2.22
A × C	1,8	3.04 0.18	8.72 * 1.48	0.41 1.34	0.82 0.02	1.85 0.02	1.30 1.34
A × D	1,64	4.80 * 3.34 *	3.14 * 9.42 *	3.72 * 2.38 *	2.53 * 5.09 *	2.65 * 0.21	2.36 * 5.50 *
B × C	1,8	0.50 1.23	8.89 * 12.57 *	0.71 0.34	1.87 3.67	0.96 0.32	7.83 * 5.42 *
B × D	8,64	28.40 * 18.05 *	3.36 * 4.37 *	1.67 2.09 *	1.27 1.74	0.86 1.93	2.07 * 1.15
C × D	8,64	17.32 * 16.79 *	1.37 3.34 *	3.48 3.96 *	2.70 * 1.42	0.18 1.96	0.42 0.63
A × B × C	1,8	4.12 2.17	5.48 * 0.31	0.01 0.07	0.07 1.01	0.95 0.14	1.38 0.46
A × B × D	8,64	1.82 3.45 *	2.27 * 5.62 *	1.89 0.74	2.61 * 2.79 *	3.96 * 1.66	1.98 2.23 *
A × C × D	8,64	2.13 * 2.48 *	5.06 * 2.06	1.20 0.57	0.61 0.89	4.12 * 0.98	2.58 * 1.45
B × C × D	8,64	30.77 * 20.55 *	1.36 2.25 *	1.93 2.23 *	0.97 0.40	0.11 1.72	0.49 0.75
A × B × C × D	8,64	0.71 2.41	2.31 * 2.32 *	1.14 0.47	1.34 0.85	5.90 * 0.45	1.77 1.31

* Significant at $P < 0.05$.

The P350 factor scores (Factor 2) are also shown in Fig. 4. Like the SW, P350 was mainly associated with rare, relevant stimuli. Frequent, relevant stimuli were associated with small P350 factor scores, and for irrelevant stimuli the P350 factor scores were small regardless of stimulus probability. Unlike for the SW, however, the size of P350 was not symmetric for loud and soft tones in the counting condition; whereas the P350 scores were large for loud tones which were rare and relevant, they were small for soft tones even when they were rare and relevant. Whether this was due to the relative intensities of the rare and frequent stimuli in each case or to the designation of the loud stimulus as the target event could not be evaluated within this analysis since the intensity and target variables were confounded. Consequently an additional factor analysis was performed on the data from Experiment II, this time including the "count soft" condition. The factors which emerged from the three-condition analysis were clearly analogous to those shown in Fig. 3, particularly in the cases of the first 4 factors. Among those conditions which were common to both analyses (all except "count soft") the variations in the factor scores as functions of signal probability and electrode site were essentially the same as shown in Fig. 4. The pertinent result, however, was that instructions to count the soft stimuli were not sufficient to enhance the rare-soft stimulus P350 to the degree shown for the rare-loud stimulus. The rare-loud P350 was also much reduced when the soft stimulus was the target (to the size of those for the rare-soft stimuli). Thus the P350 is of approximately equal amplitude for rare-loud and rare-soft stimuli in the counting conditions unless the rare-loud is the target event, in which case the P350 is much enhanced.

The presence of the SW made it impossible in the earlier study by N. Squires et al. (1975) to determine with certainty the scalp distribution of the P350. When the effect of the SW is removed by the principal components analysis

it is evident that P350 for rare, relevant stimuli is largest at C_z , next largest at P_z , and smallest at F_z . The distributions were identical in both experiments.

These results bear directly on Näätänen's three-component hypothesis. We clearly observe a long duration, "slow", process with a positive polarity at the parietal electrode. According to the time course of the factor loading function this process apparently begins to affect the ERP waveform as early as 250 msec after the stimulus. Thus it seems to be an excellent candidate for serving as Näätänen's slow positive process. Yet, this component is clearly distinct from the P350.

As was expected on the basis of previous reports (cf. Picton et al. 1974) the N100 factor was larger at the frontal and central sites than at the parietal site. Also, it was uninfluenced by variations in signal probability.

Factor 4 which, on the basis of its peak latency, was associated with the N210 peak of the ERP showed a systematic decrease in its factor score with decreasing signal probability, which is consistent with the emergence of a negative component elicited when signals were rare. These variations with signal probability can further be seen to be independent of task requirement. The fact that the factor scores were positive for highly probable signals is probably due to the residual contributions of portions of the P160 and P350 peaks which overlapped the skirts of the N210 factor loading function. The width of the N210 loading functions is undoubtedly wider than the actual duration of N210 because of slight latency differences between subjects and across conditions. As shown by the ANOVA, however, variation in the factor scores cannot be attributed solely to between-subject variance.

While Factor 6 appeared in both experiments, no ready interpretation of this factor was obvious from either the factor scores or the factor functions. Possibly it is related to the P270 peak of the ERP. Of all segments of the ERP epoch, however, the region spanned by Factor 6 is by far the most complex and

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variable across subjects (Fig. 2). Consequently, it is safest to note only that there is a consistent source of variability within this region.

Finally, due to the current interest in lateral asymmetries of ERP components (Friedman et al. 1975, Donchin et al. in press), we evaluated the extent to which such asymmetries appear in our data. No significant asymmetries were found *.

Discussion

This study has firmly established the existence of multiple sources of experimental variance within the latency range of the classical P300 component of the ERP. These factors can be differentiated on the basis of their sensitivity to experimental variables using a Principal Components analysis of the waveforms. Stimulus probability and task requirement, as well as scalp distribution appear to be major factors allowing the differentiation of the components.

One factor extracted from the data corresponds to the SW component first reported by N. Squires et al. (1975). A second was found to peak at about 350 msec post-stimulus and can be identified with the component variously labeled P300 (Smith et al. 1970; Donchin et al. 1973, 1975), P3 (Wilkinson and Morlock 1967; Hillyard et al. 1971; Karlin and Martz 1973; Squires et al. 1973; Tueting and Sutton 1973), or P3b (N. Squires et al. 1975). The present study has clarified the scalp distribution of P350 which in previous work was obscured by the presence of the SW, which affected base-to-peak measures. When the contribution of the SW is re-

moved, the P350 factor appears to have a centro-parietal maximum (Vaughan and Ritter 1970; Picton and Hillyard 1974; Donchin et al. 1975). While P350 and SW are closely related on the basis of their modes of variation under experimental manipulation (but differ in scalp distribution), they are experimentally separable. Our data show that SW is elicited by all rare, relevant stimuli while P350 is elicited mainly by rare, loud targets. Wilkinson and Ashby (1974) as well as Näätänen (1975) have suggested that the P300 component is a slow, post-preparatory, reactive positive wave. They attribute the peaked appearance of the component with a latency at 300-400 msec to various experimental artifacts. Our data show that the slow wave and P300 are quite distinct components and therefore were not consistent with Näätänen's three-component hypothesis. Of course, it is possible that the SW is not equivalent to Näätänen's "slow-positive process" but if such a process exists it has failed to materialize either in our data or elsewhere in the literature. The present results then lend further credence to the view that P300 is a distinct endogenous component of the ERP which is invoked by the task demands rather than a reactive change in global preparedness or a modulation of long-lasting waves.

Another probability-related factor was found which, on the basis of its latency (and scalp distribution), may be associated with the N210 peak of the ERP. Unlike the P350 and SW which seem to require active processing of stimulus information for their elicitation, this factor was associated with rare stimuli regardless of the subject's task requirement. A similar component (N2) was described by N. Squires et al. (1975). On the basis of the robustness of the N210 factor, it must be considered a major aspect of the ERP waveform. Whether it is related to the other, recently described, "mid-latency negative components" remains to be seen (Ford et al. 1973; Picton et al. 1974; Simson et al. 1976; Ruchkin and Sutton, in press).

Of the two remaining factors described

* Space will not allow a description of many other analyses which were performed on the data. Suffice it to say that a detailed evaluation of the correlation matrix yielded essentially the same results. Furthermore, when the results of the Varimax solution are compared with those obtained with other rotation schemes no substantial differences are observed. Readers interested in a description of these alternate analyses can contact the authors.

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here, one is a reflection of the N100 component of the auditory evoked potential. Another factor was found which, while consistent across experiments, was not significantly related to any of the main experimental variables. The peak latency of the loading function for that factor makes it a candidate for association with the P270 peak of the ERP. As described here and by N. Squires et al. (1975, p. 398), The P270 or P3a peak is the waveform feature which is the most variable across subjects. Occurring as it does at a latency where there is a mix of activity due to three dominant components (N210, P350 and SW), resolution of the P270 component may be beyond the scope of the Principal Components procedure. Another hypothesis that may be entertained is that Factor 6 and P270 are not related at all but N210 and P270 are aspects of the same process, hence non-independent. This hypothesis is not contradicted by the present data and is consistent with the base-to-peak analysis reported by N. Squires et al. The only negative evidence is from the factor analysis of the peak amplitudes reported by N. Squires et al. who found independent factors for N2 and P3a. In that analysis, however, one additional degree of freedom entered into the measurements when peak amplitudes were measured at slightly varying latencies across waveforms. Consequently, a dissociation may have been entered into the behavior of N2 and P3a. The present data can therefore be interpreted either as dependence between N200 and the P270 (P3a) or as identifying Factor 6 with P3a, in which case its failure to be affected by the experimental variables is puzzling. Be that as it may, we do find that one component of the ERP, namely N210, reflects stimulus probability independent of task while another, P350, depends on an interaction between stimulus probability and the task.

The procedures reported here highlight the utility of the Principal Components-ANOVA procedure (Donchin 1966). Here components of the ERP are interpreted with reference to the experimental variance. New components

are identified only if the voltages over a particular segment of the epoch show systematic joint variations as a function of the experimental variables. Such an analysis depends on an identification of sources of variance in the data and a determination of the extent to which each source is related to each of the experimental variables. It is important to emphasize that the Principal Components of the data matrix are not to be interpreted as representing specific neurophysiological generators or electrocortical activity. They merely serve to summarize the effects of experimental variables on the ERP waveform. But, then, there is no *necessary* relationship between any scalp measures and underlying generators. In this report, as well as in others (Donchin et al. 1975; N. Squires et al. 1975; Kutas and Donchin, *in press*), it has been shown that this staged analysis procedure provides a powerful method for objectively resolving the components of cortical ERPs.

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Summary

~~Fifteen~~
~~Eighteen~~ subjects were presented with series of tones. Any one tone was either loud or soft, and in any one series the probability of one tone intensity was either 0.9 or 0.1. Subjects were instructed to count the frequent tones or to count the rare tones. The stimuli were also presented while the subjects were solving a word-puzzle. Event-related potentials (ERPs) were recorded from 9 scalp locations (F₃, C₃, P₃, F_z, C_z, P_z, F₄, C₄, P₄) referred to linked mastoids. ERP components were measured with a Principal Components analysis and the relations between these measures and the independent variables were evaluated with the ANOVA procedure.

This paradigm allowed an evaluation of the effect of stimulus probability, stimulus relevance, and task relevance on the waveform of the ERPs. We conclude that the P350 component is enhanced whenever the eliciting stimulus is both rare and in some sense relevant to the subject's task and the degree of enhance-

ment is greatest when the rare-relevant tone is loud. A "slow wave" component which follows P350 is related to the same variables but has a scalp distribution quite different from that of P350. The slow wave shows a progressive shift in polarity from negative to positive from the frontal to the parietal sites, while the P350 is of nearly equal amplitude (and positive) at the central and parietal sites and has a smaller (positive) amplitude at F_z.

A third prominent component, negative in polarity, peaking at about 210 msec, is most pronounced following rare stimuli, whether or not they were task relevant. The amplitude of N210 tended to be largest at the frontal electrode.

This study then demonstrates that when suitable measurement techniques are used, multiple endogenous ERP components can be observed, each related to distinct aspects of cognitive behavior.

Résumé

Influence de l'adéquation de la tâche et de la probabilité du stimulus sur les composantes de ERP

On présente une série de sons à 18 sujets. Chaque son est soit fort, soit doux, et dans chaque série la probabilité d'intensité d'un son particulier est soit 09 soit 01. Il est demandé au sujet de compter les sons les plus fréquents ou de compter les sons rares. Les stimulus sont également présentés lorsque les sujets sont en train de résoudre un puzzle de mots. Les potentiels liés aux événements (ERP) sont enregistrés sur 9 électrodes de scalp (F₃, C₃, P₃, F_z, C_z, P_z, F₄, C₄, P₄), reliées à une électrode bimastoidienne. Les composantes du ERP sont mesurées au moyen d'une Analyse en Composantes Principales et les relations entre ces mesures et les variables indépendantes sont évaluées au moyen de la procédure ANOVA.

Ce paradigme permet une évaluation de l'effet de la probabilité du stimulus, de l'adé-

quation du stimulus, et la pertinence de la tâche sur la morphologie des ERPs. Les auteurs concluent que la composante P350 est augmentée chaque fois que le stimulus qui la déclenche est à la fois rare et d'une certaine manière pertinent, et le degré d'accroissement est d'autant plus grand que le son rare et pertinent est fort. Une composante "onde lente" consécutive au P350 est liée aux mêmes variables mais présente une distribution sur le scalp tout à fait différente de celle du P350. Cette onde lente montre un changement progressif de polarité, de la négativité à la positivité, entre les régions frontales et pariétales alors que le P300 est d'amplitude à peu près égale (et positive) au niveau des localisations centrales et pariétales et a une amplitude moindre (positive) au niveau de F_z.

Une troisième composante importante, de polarité négative, dont le pic se situe à environ 210 msec, est plus prononcée après des stimuli rares, qu'ils soient ou non pertinents pour la tâche.

L'amplitude du N210 tend à être la plus grande au niveau de l'électrode frontale. Cette étude montre donc que, lorsque des techniques de mesures adéquates sont utilisés, de multiples composantes endogènes du ERP peuvent être observées, chacune d'elles étant liée à des aspects distincts du comportement cognitif.

We thank Martha Kutas and Terrence R. Dunn for helpful comments on previous versions of this report.

References

- Davis, H. Slow cortical responses evoked by acoustic stimuli. *Acta otolaryng.* (Stockh.), 1965, 59: 179-185.
- Dickman, K.W. Soupac program descriptions. DCL Report No. UIUCDCS-R-72-370-4, University of Illinois, Urbana-Champaign, 1974.
- Dixon, W.T. BMDP biomedical computer programs. University of California Press, Los Angeles, Calif., 1975.

Marta

- Donchin, E. A multivariate approach to the analysis of average evoked potentials. *IEEE Trans. biomed. Engng.*, 1966, 13: 131-139.
- Donchin, E. Data analysis techniques in evoked potential research. In E. Donchin and D.B. Lindsley (Eds.), *Average evoked potentials: Methods, results, evaluation*. NASA SP-191, Government Printing Office, Washington, D.C., 1967.
- Donchin, E., Callaway, E. and Jones, R. Auditory evoked potential variability in schizophrenia. II. The application of discriminant analysis. *Electroenceph. clin. Neurophysiol.*, 1970, 29: 429-440.
- Donchin, E., Kubovy, M., Kutas, M., Johnson Jr., R. and Herning, R.I. Graded changes in evoked response (P300) amplitude as a function of cognitive activity. *Percept. Psychophys.*, 1973, 14: 310-324.
- Donchin, E., Tueting, P., Ritter, W., Kutas, M. and Heffley, E. On the independence of the CNV and the P300 components of the human averaged evoked potential. *Electroenceph. clin. Neurophysiol.*, 1975, 38: 449-461.
- Donchin, E. and Heffley, E. Minicomputers in the signal averaging laboratory. *Amer. Psychol.*, 1975, 30: 299-312.
- Donchin, E. and Herning, R.I. A simulation study of stepwise discriminant analysis in the detection and comparison of event related potentials. *Electroenceph. clin. Neurophysiol.*, 1975, 38: 51-68.
- Ford, J., Roth, W., Dirks, S. and Kopell, B. Evoked potential correlates of signal recognition between and within modalities. *Science*, 1973, 181: 465-466.
- Harmon, H.H., *Modern factor analysis*. The university of Chicago Press, Chicago, Ill., 1967.
- Harshman, R.S. Foundations of the Parafac procedure: Models and conditions for an "explanatory" multi-modal factor analysis. Working Papers in Phonetics No. 16. Univ. of Calif. at Los Angeles, December, 1970.
- Hillyard, S., Squires, K., Bauer, J. and Lindsay, P. Evoked potential correlates of auditory signal detection. *Science*, 1971, 172: 1357-1360.
- John, E.R., Ruchkin, D.S. and Villegas, H. Experimental background: Signal analysis and behavioral correlates of evoked potential configuration. *Ann. N.Y. Acad. Sci.*, 1964, 112: 362-420.
- John, E.R., Walker, P., Cawood, D., Ruch, M. and Gehrman, J. Factor analysis of evoked potentials. *Electroenceph. clin. Neurophysiol.*, 1973, 34: 33-34.
- Karlin, L. and Martz Jr., M. Response probability and sensory evoked potentials. In S. Kornblum (Ed.), *Attention and performance IV*. Academic Press, New York, 1973.
- Keppel, G. *Design and analysis: A researchers handbook*. Prentice Hall, Englewood Cliffs, N.J., 1973: 393-474.
- Kutas, M. and Donchin, E. The effect of handedness, the responding hand, and response force on the contralateral dominance of the "readiness" potential. In J. Desmedt (Ed.), *Proc. Int. Symp. Cerebral Evoked Potentials in Man*, Brussels, 1974, in press.
- McCarthy, G. and Donchin, E. The effects of temporal and event uncertainty in determining the waveform of the auditory event related potential. ~~Paper presented to the Society for Psychophysiological Research, Toronto, 1975.~~ *in press.*
- Näätänen, R. Selective attention and evoked potentials in humans - a critical review. *Behav. Biol.*, 1975, 2: 237-307.
- Picton, T.W. and Hillyard, S.A. Human auditory evoked potentials. II: Effects of attention. *Electroenceph. clin. Neurophysiol.*, 1974, 36: 191-199.
- Picton, T.W., Hillyard, S.A., Krausz, H.I. and Galambos, R. Human auditory evoked potentials. I: Evaluation of components. *Electroenceph. clin. Neurophysiol.*, 1974, 36: 179-190.
- Price, R.L. and Smith, D.B.D. the P₃₀₀ wave of the average evoked potential: A bibliography. *Physiol. Psychol.*, 1971, 2: 387-391.
- Ruchkin, D. and Sutton, S. Latency characteristics and trial by trial variation of emitted potentials. In J. Desmedt (Ed.), *Proc. Int. Symp. Cerebral Evoked Potentials in Man*, Brussels, 1974, in press.
- Simson, R., Vaughan Jr., H.G. and Ritter, W. The scalp topography of potentials associated with missing visual or auditory stimuli. *Electroenceph. clin. Neurophysiol.*, 1976, 40: 33-42.
- Smith, D.B.D., Donchin, E., Cohen, L. and Starr, A. Auditory averaged evoked potentials in man during selective binaural listening. *Electroenceph. clin. Neurophysiol.*, 1970, 28: 146-152.
- Squires, K.C., Hillyard, S.A. and Lindsay, P.H. Cortical potentials evoked by confirming and disconfirming feedback following an auditory discrimination. *Percept. Psychophys.*, 1973, 13: 25-31.
- Squires, N., Squires, K. and Hillyard, S. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroenceph. clin. Neurophysiol.*, 1975, 38: 387-401.
- Tueting, P. and Sutton, S. The relationship between pre-stimulus negative shifts and post-stimulus components of the averaged evoked potential. In S. Kornblum (Ed.), *Attention and performance IV*. Academic Press, New York, 1973.
- Vaughan Jr., H.G. and Ritter, W. The sources of auditory evoked responses recorded from the human scalp. *Electroenceph. clin. Neurophysiol.*, 1970, 28: 360-367.
- Wilkinson, R.T. and Ashby, S.M. Selective attention, contingent negative variation and the evoked potential. *Biol. Psychol.*, 1974, 1: 167-179.
- Wilkinson, R.T. and Morlock, R. Auditory evoked response and reaction time. *Electroenceph. clin. Neurophysiol.*, 1967, 23: 50-56.

Donchin, E., Kutas, M. and McCarthy, G. Electroencephalographic indices of hemispheric utilization. In S. Harnad (Ed.), *Lateralization in the nervous system*. Academic Press, New York, in press.

Freeman, D., Simson, R., Ritter, W. and Papp, I. Cortical evoked potentials and auditory reaction time. *Electroenceph. clin. Neurophysiol.*, 1975, 38: 13-19.



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BEYOND AVERAGING: THE USE OF DISCRIMINANT FUNCTIONS TO RECOGNIZE EVENT RELATED POTENTIALS ELICITED BY SINGLE AUDITORY STIMULI *

KENNETH C. SQUIRES and EMANUEL DONCHIN

University of Illinois, Champaign, Ill. 61820 (U.S.A.)

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An estimate of the waveform of cortical event related potentials (ERPs) can be obtained when an ensemble of EEG epochs, each anchored to the instant at which the event occurred, is averaged. Such ensemble averages have been studied extensively in the past decade and have provided valuable information (Regan 1972; Price and Smith 1974). However, the interpretation of the waveform of an averaged ERP rests on the assumption that all realizations of the event are essentially identical. This assumption is not always tenable; to each specific occurrence of an event a subject may react differently. When behavioral consequences are measured precisely, considerable variability is shown even over repeated presentations of the "same" event: reaction times vary, different associations are invoked, and expectations that an event will occur vary from trial to trial. Since experimental manipulations which affect mean reaction times, decision process, and expectancies for ensembles of events are known to influence profoundly the waveform of the ERP associated with the ensembles, trial-to-trial variations in these same variables are likely to manifest themselves in trial-to-trial variations in the

ERP. The investigations of intertrial variability in the waveforms encounter formidable problems, however, as the potentials associated with any single event are small relative to the ongoing EEG activity.

Some investigators have tried to sort experimental trials by their behavioral consequences (Donchin and Lindsley 1966; Hillyard et al. 1971; Paul and Sutton 1972), hoping that the resulting averages will yield better estimates of the waveforms of the ERPs associated with different classes of trials. This technique, however, depends upon the initial selection of a trial-sorting procedure, as quite different averaged waveforms may be obtained when different sorting procedures are used (Squires et al. 1973). Clearly it would be useful to have a technique whereby trial-to-trial assessments of evoked potential waveforms can be performed and sorting done on the basis of categorizations of individual trials. Complementary analyses of the ERPs sorted by waveform variations and by behavioral response variations should aid in investigating the relationships between evoked potentials and levels of stimulus processing.

A technique for classifying single-trial evoked potentials utilizing stepwise discriminant analysis (SWDA) has been proposed by Donchin (1969) and evaluated in some detail by Donchin and Herning (1975). Briefly stated, the procedure takes sets of EEG epochs known to be associated with particular events (training sets) and extracts a classification rule such that new records, known to be members of one of the parent populations (test set), can

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be classified. The discriminant function has been used as a measure of differences between average waveforms (Donchin et al. 1973), but its application to the analysis of single-trial records has been illustrated in the past using small data sets (Donchin 1969). It has not yet been evaluated against an extensive data base obtained from a number of subjects in a variety of experimental conditions. We report here such an evaluation of the efficacy of the SWDA procedure using an extensive data base provided by two recently completed studies Donchin et al. (1975) Squires et al. ~~submitted for publication (a)~~.

Methods

The data were collected in the study described in detail by Squires et al. ~~(submitted for publication (x))~~. The subjects counted tones (1000 c/sec, 50 msec duration) of a particular intensity which were substituted for members of a train of regularly occurring tone bursts of another intensity. Subjects could easily discriminate between the two intensities. Every 1300 msec a tone of one of the two possible intensities was presented to the subject through earphones. The data reported here were obtained when 90% of the tones were of a low intensity (60 dB SPL, against a continuous background of wide-band noise at 55 dB SPL). The subjects was either to count the loud tones, and verbally report their number after a block of 200 trials or to ignore all tones and solve a hidden word puzzle. In each condition, either 400 or 600 trials were presented yielding approximately 40-60 presentations of the rare loud stimulus. Single-trial EEG data from sixteen subjects in that study were available for analysis.

The discriminant functions (DFs) developed on this training set were tested both on the data from which they were derived and on another data set (the test sets) collected in a different experiment, described by Donchin et al. (1975), using different subjects. The procedures for generating this test set were

quite similar to those in the training set experiment except that the subjects counted tones which differed in frequency (2000 vs. 1000 c/sec) rather than intensity. Frequency changes in such an experiment have been shown to elicit averaged waveforms which are essentially identical to those elicited by intensity shifts (Squires et al. 1975). Six subjects participated in the second experiment. The data from an additional subject who participated in the first experiment but whose data were not available for the initial analysis for technical reasons were also added to the set of "new" single-trial waveforms.

On each trial a 768 msec epoch of EEG was digitized at the rate of one sample every 3 msec and stored on magnetic tape. The epoch began 100 msec prior to stimulus onset. While the EEG was recorded from nine scalp locations, this report will deal with the data recorded at F_z, C_z, and P_z (according to the 10-20 system) referred to linked mastoids. The EEG was amplified with Grass 7P122 amplifiers (time constant 0.8 sec and upper half-amplitude frequency 60 c/sec).

The data were scanned and epochs containing EOG artifacts were deleted from all analyses. The data base contained an equal number of epochs elicited by rare-loud and frequent-soft stimuli for each of the three electrode sites. This, of course, required that the records associated with many of the frequent stimuli be eliminated, thus the epochs associated with every ninth artifact-free frequent stimulus were used*. For the discriminant analysis 64 values were used per epoch, which were obtained by averaging over four successive time points.

* The deletion of this substantial number of records associated with frequent stimuli was dictated by economic considerations. The cost of processing all of the single trials would have been prohibitive. Note that the "frequent" trials selected were distributed evenly during the experimental session. In a related study in this laboratory Duncan-Johnson and Donchin (in preparation) did not find systematic differences between ERPs based on frequent stimuli selected from different segments of a run.

The SWDA procedure has been described elsewhere (Donchin 1966; Donchin et al. 1970; Donchin and Herning 1975; See Dixon 1975 for specific details). The SWDA analyses described were performed at the Campus Computing Network at UCLA using the BMDP7M stepwise discriminant analysis program (Dixon 1975). All classification percentages we report are based on the "Jackknife" classification procedure (Dixon 1975). In previous studies we often utilized the BMD07M version of program. While the P- and O-series of BMD differ in important ways, the programs use essentially equivalent computational procedures. Direct comparison of the results obtained when the two programs were applied to the same data sets fail to reveal any differences. Here the input to the program consisted of the set of digitized single trials from pairs of conditions (e.g., rare-loud and frequent-soft from a particular electrode site). A subsequent analysis using data generated by the second set of subjects was performed at the University of Illinois on a PDP 11/40.

Results

Classification performance of SWDA

Nine separate discriminant functions (DFs) were made for each subject. The first set of three DFs (one for each electrode site) was computed from training sets containing waveforms associated with rare-loud stimuli and waveforms associated with frequent-soft stimuli. Both stimuli were presented within one sequence of trials in which the subject counted the number of occurrences of the loud stimulus. The DFs developed on the basis of these training sets will discriminate between the ERPs elicited by rare and by frequent stimuli, which are known to differ mostly in the P300 component of the ERP. The averaged ERPs for both groups of the training set for one subject at C₂ are shown in Fig. 1, comparison 1.

A second set of three DFs was constructed

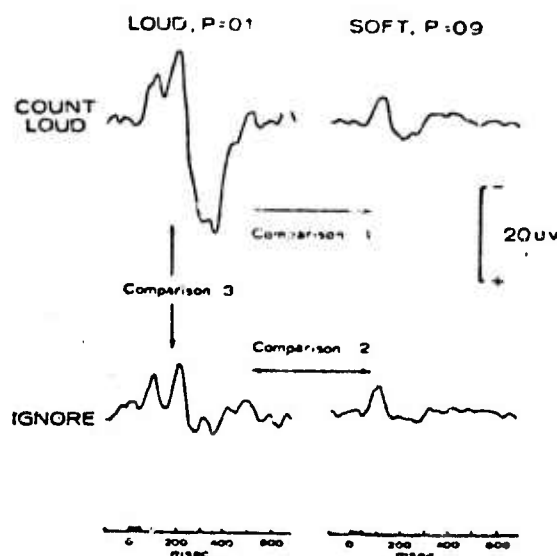


Fig. 1. Average ERP waveforms from single-trial data sets for one subject. The polarity convention is negative up.

from a training set composed of waveforms associated with rare-loud and frequent-soft stimuli presented when the subject was solving the hidden-word puzzle (the "ignore" condition), thus both tones were irrelevant. A DF so developed should allow a discrimination between rare and frequent events in the background of the subject's attention. A pair of averaged ERPs for that training set is shown in Fig. 1, comparison 2. The third set of DFs was constructed from a training set of epochs associated with the rare-loud stimulus in two conditions: when the subjects counted that stimulus and in the "ignore" condition (comparison 3).

The variations in ERP waveshapes shown in Fig. 1 have been documented and discussed elsewhere (Squires et al. 1975; ~~submitted for publication~~ ^{in press (a)}). For the purpose of this study, the ERP waveshapes shown in Fig. 1 encompass the range of waveform variation commonly encountered in the study of the ERP and provide an apt test of the efficacy of the SWDA procedure in classifying single-trial waveforms.

In the initial analysis we performed three separate discriminations for each subject for each of the three electrode sites. The results of these analyses are presented in Table I. It should be emphasized that the program discriminates between two groups of epochs defined according to stimuli presented to the subjects, not according to the subjects' responses. As will be shown below this sense of "correct" classification may obscure the full power of the DF technique.

When subjects counted the loud stimuli (comparison 1) the SWDA analysis classified correctly an average of 84% of the waveforms across all electrodes (range 68–96). The best average classification performance was found at the C_2 electrode (86% correct); however, this varied from subject to subject and the differences between electrodes were not statistically significant ($F(2,30) = 2.36$, $P > 0.05$). In the analogous condition in which the auditory signals were task irrelevant, the mean percent correct over all electrodes was 74 (range 64–95); again there were no significant differences between electrodes ($F(2,30) = 0.80$, $P > 0.05$). For the comparison of rare-loud stimuli when they were counted versus when they were irrelevant the classification yielded a mean level of 77 (range 62–93) percent correct, with no significant differences across electrodes ($F(2,30) = 2.27$, $P > 0.05$).

Multiple electrode procedures

It is evident from Table I that the classification can be affected by the choice of electrode site for each subject; for instance, for the comparison 1 there was a mean classification performance difference of 7 percentage points between the best and worst electrode for each subject, ranging up to 13%. However, since the average classification performance was approximately equal across electrodes there is no a priori reason for selecting one site over the others. It seemed useful to devise a procedure which could be applied uniformly without a pretest procedure to determine a favourable recording site for each subject. The

approach taken was to utilize the information from multiple electrode sites.

Two different multiple-electrode decision rules were tested. One was a voting rule: if the DFs for two electrodes yielded decisions which differed from the third, the majority ruled. The results of this re-analysis are shown in Table I. There was a significant overall improvement in the classification performance for the voting rule over the performance for individual electrode sites ($P < 0.01$ for all comparisons, two-tail t test for matched pairs). On the average, the voting rule correctly classified 5% more trials than were classified using individual electrodes.

A second decision rule bases upon the values of the a posteriori probabilities of group membership was also used. The a posteriori probability of each waveform is conveniently included in the output of the SWDA program (see Donchin et al. 1970; Donchin and Herning 1975, for a discussion of these probabilities). The probabilities of group membership for two groups are, of course, complementary and the standard decision rule is to associate the waveform with the group for which the a posteriori probability is greater than 0.5. A potential advantage in using a combination rule based upon the a posteriori probabilities over the previously described voting rule is that the probability statistics are continuous between 0.0 and 1.0 and can be considered a measure of the "confidence" with which the waveform is ascribed to one group or another. In this case the rule was that an average a posterior probability of greater than 0.5 across the three electrodes sufficed to classify a trial. The results are also shown in Table I. The discriminant performance for the averaging rule was significantly better than that for the individual electrodes ($P < 0.01$, t test for matched pairs) and was essentially the same as for the voting rule.

Information from the multiple electrodes can also be utilized by combining the waveforms prior to classification. Using data sets made up of potentials averaged across the three electrode sites, 85% of the waveforms from

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TABLE I

Percent correct classifications.

Sub- jects	Rare—loud vs. frequent—soft, count loud					Rare—loud vs. frequent—soft, irrelevant					Rare—loud, count loud vs. irrelevant					
	F ₂	C ₂	P ₂	Vote	Average proba- bility	Average wave	F ₂	C ₂	P ₂	Vote	Average proba- bility	F ₂	C ₂	P ₂	Vote	Average proba- bility
1	85	86	73	90	94	81	70	71	63	74	73	78	77	72	81	79
2	86	86	93	89	89	85	71	79	81	81	83	80	74	84	85	84
3	77	76	78	83	83	82	68	69	66	74	75	71	79	78	84	82
4	82	92	95	95	91	91	75	68	72	73	73	74	90	93	90	91
5	79	80	80	87	87	81	77	71	66	72	75	75	74	78	79	77
6	79	84	85	85	87	84	73	75	73	78	79	75	80	79	81	84
7	85	84	82	86	89	84	81	80	75	82	82	78	70	78	82	87
8	79	78	68	79	81	78	78	77	61	80	82	65	74	74	80	75
9	78	79	84	85	87	79	64	68	66	74	76	62	63	77	77	72
10	89	95	89	96	93	95	77	88	78	85	84	76	85	88	85	86
11	96	93	85	95	96	91	68	77	76	76	80	84	79	78	81	82
12	83	86	80	95	85	87	74	77	74	80	78	80	83	83	90	86
13	80	84	84	89	89	85	64	68	79	76	79	84	90	90	93	91
14	75	86	83	86	83	81	93	95	95	95	95	87	80	78	88	85
15	82	86	76	86	87	86	66	70	74	81	84	73	76	72	82	82
16	93	96	96	97	97	96	78	73	76	80	80	87	91	84	93	95
Mean	83	86	83	88	89	85	74	75	74	79	80	77	79	80	84	84
S.D.	6	6	8	5	5	5	7	8	8	6	6	7	8	6	5	6

rare-loud versus frequent-soft stimuli in the counting conditions were classified correctly (Table I). This was the same as for best single electrode analysis (as C_z), but it eliminated the occasionally low performance scores found in the single-electrode analyses.

Distribution of time points

While the classification performance measures for the SWDA procedure were approximately equal in each condition across the three electrode sites, the DFs were based upon different sets of time points * at each electrode. That is, the points which optimally discriminated between the conditions were found to vary from one electrode position to another. Since the waveforms themselves differ markedly along the midline from parietal to frontal sites due to variations in the size of the constituent components, this finding was expected and the results support the findings of previous studies using this experimental procedure (Squires et al. 1975, submitted for publication (x)). It is important, however, to evaluate the extent to which the time points selected for the different subjects are randomly scattered across the epoch or are concentrated in some specific regions of the epoch. As Donchin et al. (1970) have noted, unless the time points selected show some systematic relation to ERP components, the discriminant function cannot be taken to reflect substantive differences between the ERP waveforms.

The distribution of time points that were found to discriminate best conditions in the three classifications can be summarized by looking at the first two latency points selected for each subject. The voltages of these latencies tend to be more powerful in discriminating between conditions. Histograms were constructed for each comparison according to the latencies of the points measured from stimulus onset. In Fig. 2 the histogram bins roughly correspond to the components of the ERP.

* The terms "time point" or "point" are used here as synonyms for "variable" in the parlance of BMDP7M.

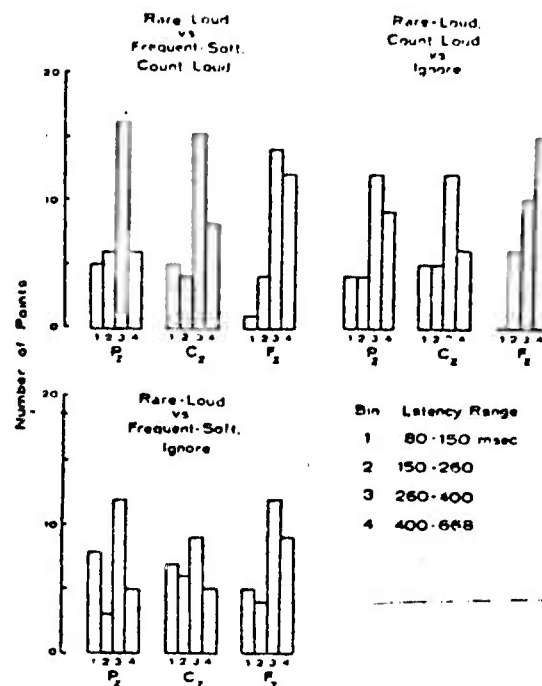


Fig. 2. Latency histograms for first two time points extracted in the discriminant analyses.

The first bin extends from 80 to 150 msec and encompasses the N100 components. Bin two extends from 150 to 260 msec, encompassing the N210 component, and bin three (260-400 msec) encompasses the P350 (or P300) component. Bin four (400 msec and greater) spans the range of the slow wave component (SW).

In the comparison in which rare-loud stimuli were counted, there is a peak in the histogram for the P350 bin at all electrode sites; and there is a trend for more points to be selected from the SW bin as the recording site varies from P_z to F_z . A similar result is seen for the rare-loud, counting versus ignore comparison. In the comparison where all stimuli are irrelevant the selection of points is more uniformly distributed in time. The tendency for the SW points to be selected more often and the N100 points to be selected less often holds, but more points are picked from N100 and fewer from the SW than in the other

TABLE II

Latencies and weighting coefficients for the subject-independent discriminant functions. The latencies are referred to stimulus onset and the weighting functions are for voltages in arbitrary units referred to a baseline voltage over the 100 msec period pre-stimulus onset. The equation for the discriminant function is: $DF = \sum_{j=1,6} a_j X_{ij(j)}$, where $X_{ij(j)}$ is the voltage at latency $i(j)$ (in msec) and $a(j)$ is the weighting applied to that voltage value.

Electrode site		j = 1	2	3	4	5	6
P _z	Latency, i(j)	104	188	248	320	356	380
	Weight, a _j	-0.00209	-0.00247	-0.00422	0.00346	0.00364	0.00349
C _z	Latency, i(j)	128	236	332	356	380	668
	Weight, a _j	-0.00332	-0.00258	0.00395	0.00409	0.00234	-0.00349
F _z	Latency, i(j)	224	344	380	476	536	572
	Weight, a _j	-0.00327	0.00850	0.00355	-0.00305	-0.00301	-0.00315

conditions. The results of the three comparisons are consistent with the waveform differences shown in Fig. 1 and the topographical distributions for the major components which have been described previously (c.f., Squires et al. 1975).

Subject-independent SWDA

The preceding analyses were all within-subject procedures. Such a personalized treatment can be useful for discriminating single-trial ERPs in many situations of experimental interest; however, a generalized procedure which is applicable to all subjects in this and future experiments would obviously be useful. As a first step toward such a procedure, DFs were computed for each electrode site for all trials associated with rare-loud and frequent-soft stimuli when loud stimuli were counted regardless of subject. These are shown in Table II. The first time point selected for the group function was one at 356 msec for P_z and C_z and one at 344 msec for F_z. The second points were at 248 for P_z, 668 for C_z and 572 for F_z. The results for each electrode site are shown in Table III. Clearly the group function was less successful at classifying trials for each subject than were the individual fun-

ctions. Remarkable, the decrease in discrimination performance was only about 7%, from 34% for the individual function mean to 77% for the group mean across electrodes.

TABLE III

Percent correct for subject-independent DF. Rare-loud vs. frequent-soft, count loud.

Subjects	F _z	C _z	P _z
1	72	71	66
2	73	80	80
3	74	80	71
4	82	85	95
5	69	76	78
6	81	80	79
7	69	79	85
8	73	76	75
9	65	75	69
10	76	76	88
11	74	81	75
12	70	72	79
13	76	77	77
14	77	74	73
15	82	77	76
16	80	78	78
Mean	75	77	78
S.D.	5	4	7

Applying the group function to new subjects

Using a PDP11/40 computer, the digitized waveforms from comparison 1 for seven new subjects were read off tape and the group discriminant functions for each electrode site were applied. The discriminant function weightings of Table II were multiplied by the single-trial waveform voltages at the appropriate latencies, thus yielding a statistic (discriminant score) to which a decision rule was applied. Since trial waveforms with discriminant scores greater than a criterion level determined during the calculation of the group discriminant function were classified as having been elicited by rare-loud stimuli and those which were smaller were classified as elicited by frequent-soft stimuli. It was possible to use the SWDA-determined criterion directly since the new data were collected in a manner identical to the original data and, thus, required no rescaling. (If the DFs of Table II were applied to data collected with a different amplification, the data would have to be scaled appropriately or a new criterion level adopted.) The results, shown in Table IV, indicate that the subject-independent group function is as effective in classifying the new data as it was in the case of the data from which it was de-

rived. For the new group the mean classification performance was nearly identical to that for the original group, 76% correct. Evidently the original sample of sixteen subjects (training set) was large enough to create a generalizable group function.

As was the case for the original set of data, a decision rule based upon information from the three electrode sites was found to improve the precision of the classifications. By averaging the discriminant scores across electrodes prior to applying the decision rule (a procedure analogous to the averaging rule used previously), the mean classification performance across subjects was raised to 81% correct.

Discussion

From the previous analyses it is clear that the SWDA procedure for classifying single-trial auditory evoked potentials can be used with a high degree of reliability in contexts familiar to evoked potential research. When waveform differences are quite pronounced, as were those between the evoked potentials elicited by rare-loud and frequent-soft stimuli which are task relevant, correct classifications were made on 89% of the trials when subject-specific DFs in conjunction with a simple procedure for utilizing the waveforms from three electrode sites were used.

In a more general procedure in which discriminant functions are developed on the basis of one set of data and applied to another, a respectable 81% of the trials were shown to be correctly classified on the basis of three electrode sites. These results undoubtedly do not reach the level which might be obtained with an optimum procedure; in fact they are conservative since no attempt was made to optimize the decision criterion (which was derived from the group function) for each subject, yet they indicate that the procedure may be a feasible one for classifying single-trial evoked potentials on-line in experimental situations. Once discriminant functions have been computed on a representative set they

TABLE IV

Percent correct for subject-independent DF applied to new subjects.

Subjects	F ₂	C ₂	P ₂	Average discrim. score
17	77	79	83	85
18	78	72	74	80
19	83	78	80	84
20	66	70	69	74
21	66	74	77	76
22	77	77	80	82
23	83	82	83	84
Mean	76	76	78	81
S.D.	7	4	5	4

BEYOND AVERAGING

can be readily applied to subsequently acquired waveforms. At the present time the initial computation of an appropriate DF requires access to large computing facilities but once developed, application of the function presents a computational load which is well within the capability of mini-computers commonly used in evoked potential research.

It should be noted that the algorithm's performance is evaluated here using a somewhat arbitrary definition of the correctness of classification. That is, the DF had to identify the value of the signal that was actually presented in order to be considered correct. Thus the assumption is made that the subjects always respond to a rare stimulus as if it is rare and to a frequent stimulus as if it is frequent. Under such an assumption the principal source of classification errors is the level of EEG activity present at the time of signal occurrence. It is conceivable, however, that some rare stimuli evoke a "frequent" ERP and vice versa. In such a case, the program does not "err" if it classified a rare stimulus as frequent. In fact, it tends to reveal the fine structure of the subject's behavior which is obscured in group averages. In order to determine whether this indeed was the case, ERP waveforms were computed for each category of stimulus and classification and are illustrated in Fig. 3 for the rare-loud vs. frequent-soft, attend classification. Here the ERP is taken across all subjects in order to have sufficient classification "errors" for a clear ERP waveform. If the misclassified trials had been due merely to variations in the ongoing EEG, similar averaged waveforms would have been generated for each stimulus regardless of the classification. Clearly that was not the case. As has been reported by Donchin (1969), the misclassifications seem to represent differences in the ERP waveform from trial-to-trial. Rare stimuli classified as frequent fail to elicit a P300 while frequent stimuli classified as rare elicited an ERP with a P300. While this analysis suggests that the DF is quite good at classifying single-trial waveforms, the significance of these variations in terms of the subject's behavior can-

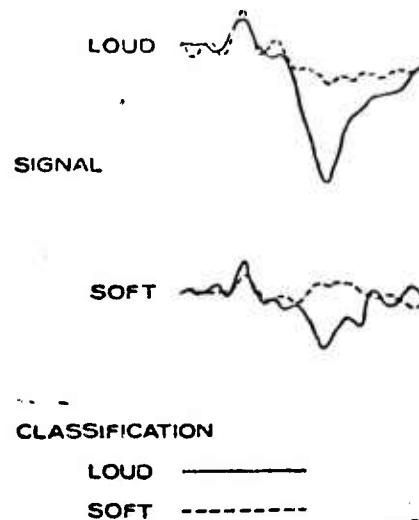


Fig. 3. Average ERP waveforms sorted according to stimulus presentation and stimulus classification by discriminant function. Average across data sixteen subjects.

not be directly assessed here since a simultaneous trial-by-trial behavioral response was not recorded. A clue to the source of the variations was found, however, through a selective-averaging analysis of portions of the data. The results strongly suggest that the discriminant score for each ERP is closely related to the pattern of stimuli preceding it. This topic is treated in detail elsewhere (Squires et al. ~~submitted for publication (b))~~ ^{in press}). For the present, these results indicate the potential usefulness of the technique for evaluating trial-to-trial variations in stimulus processing other than through an overt behavioral response by the subject.

Summary

A test of the stepwise discriminant analysis (SWDA) procedure for assessing single-trial event related potentials (ERPs) is presented. Discriminant functions (DFs) were built from a data base composed of single-trial ERPs from sixteen subjects who were presented trains of loud and soft tones. Loud tones

occurred randomly on 10% of the trials. Subjects either counted the rare-loud stimuli or solved a hidden-word puzzle. Various DFs at three electrode sites (F_z , C_z and P_z) were obtained to assess the feasibility of performing pairwise discriminations between the various combinations of events which are defined by this procedure. For the pair of events which yielded the most striking differences between their average ERP waveforms it was possible to classify correctly, an average of 84% of the events using information from one electrode site, and 89% of the events if information from multiple electrode sites was used. A "subject-independent" DF was developed from these data and applied to data obtained from seven new subjects. This subject-independent function proved to be sufficiently generalized to classify correctly 81% of the trials. The nature of classification errors by this procedure are discussed.

Resume

Au-delà du moyennage: l'utilisation des fonctions discriminantes pour reconnaître des potentiels liés à un événement, évoqués par stimulus auditif isolé

Un procédé de test d'analyse discriminante pas-à-pas (SWDA) est présentée, qui sert à mesurer des potentiels liés à un événement (ERPs) sous forme de stimulus unique. Les fonctions discriminantes (DFs) sont construites à partir d'une donnée de base composée de ERPs après stimulus unique chez 16 sujets à qui ont été présentés des trains de sons forts et légers. Les sons forts surviennent de façon aléatoire 10% des essais, la consigne donnée aux sujets est soit de compter les stimuli rares et forts, soit de résoudre un puzzle de mots cachés. Différentes DFs ont été obtenues à trois sièges d'électrodes (F_z , C_z et P_z) pour mesurer la possibilité de réalisation de discrimination par paires entre les diverses combinaisons d'événements qui sont définis par cette procédure. Pour la paire d'événements pour

laquelle les différences de morphologie des ERPs moyens sont les plus frappantes, il est possible de classer correctement en moyenne 84% des événements à l'aide d'informations venant d'un siège d'électrode et 89% des événements si l'information provenant de plusieurs électrodes est utilisée. Une DF "indépendante du sujet" est développée pour ces données et appliquée aux données obtenues chez 7 nouveaux sujets. Cette fonction "indépendante du sujet" s'avère suffisamment généralisée pour classer correctement 81% des séquences. La nature des erreurs de classification venant de cette procédure est discutée.

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References

- Dixon, W.T. BMDP biomedical computer programs. University of California Press, Los Angeles California, 1975.
- Donchin, E. A multivariate approach to the analysis of averages evoked potentials. IEEE trans. biomed. Eng., 1966, 13: 131-139.
- Donchin, E. Data analysis techniques in evoked potential research. In E. Donchin and D.B. Lindsley (Eds.), Averaged evoked potentials: methods, results, evaluation. NASA SP-191, Government Printing Office, Washington, D.C., 1969.
- Donchin, E. and Herning, R. A simulation study of stepwise discriminant analysis in the detection and comparison of event related potentials. Electroenceph. clin. Neurophysiol., 1975, 38: 51-68.
- Donchin, E. and Lindsley, D.B. Average evoked potentials and reaction times to visual stimuli. Electroenceph. clin. Neurophysiol., 1966, 20: 217-223.
- Donchin, E., Callaway, E. and Jones, R. Auditory evoked potential variability in schizophrenia. II. The application of discriminant analysis. Electroenceph. clin. Neurophysiol., 1970, 29: 429-440.
- Donchin, E., Squires, N., Squires, K. and Grossberg, S. Redundant information in auditory and visual modalities: Inferring decision related processes from the P300 component. Paper presented at Fifth Ann. Meeting Soc. Neurosci., New York, N.Y., 1975.
- Hillyard, S., Squires, K., Bauer, J. and Lindsay, P. Evoked potential correlates of auditory signal detection. Science, 1971, 172: 1357-1360.

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Donchin, E., Kutas, M., Kutas, M., Johnson Jr., R.
and Herning, R. Graded changes in evoked
potentials and reaction times to visual stimuli.
Electroenceph. clin. Neurophysiol., 1973,
14: 319-326.

- Paul, D. and Sutton, S. Evoked potential correlates of response criterion in auditory signal detection. *Science*, 1972, 177: 362-369.
- Price, R.L. and Smith, D.B.D. The P₃₀₀ wave of the average evoked potential: A bibliography. *Physiol. Psychol.* 1974, 2: 387-391.
- Regan, D. Evoked potentials in psychology, sensory physiology and clinical medicine. Wiley, New York, 1972.
- Squires, K., Donchin, E., Herning, R. and McCarthy, G. On the influence of task relevance and stimulus probability on ERP components. Submitted for publication (a). *Electroenceph. clin. Neurophysiol.*, in press (a).
- Squires, K., Hillyard, S. and Lindsay, P. Vertex potentials evoked during auditory signal detection: Relation to decision criteria. *Percept. Psychophys.* 1973, 14: 265-272.
- Squires, K., Wickens, C., Squires, N. and Donchin, E. The effect of stimulus sequence on the waveform of the cortical event-related potential. Submitted for publication (b). *Science*, in press (b).
- Squires, N., Squires, K. and Hillyard, S. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroenceph. clin. Neurophysiol.*, 1975, 38: 387-401.